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TECHNICAL REPORT GL-79-23

GEOTECHNICAL CONTAINMENT ALTERNATIVES FOR INDUSTRIAL WASTE BASIN F ROCKY MOUNTAIN ARSENAL DENVER, COLORADO; A QUANTITATIVE EVALUATION

by

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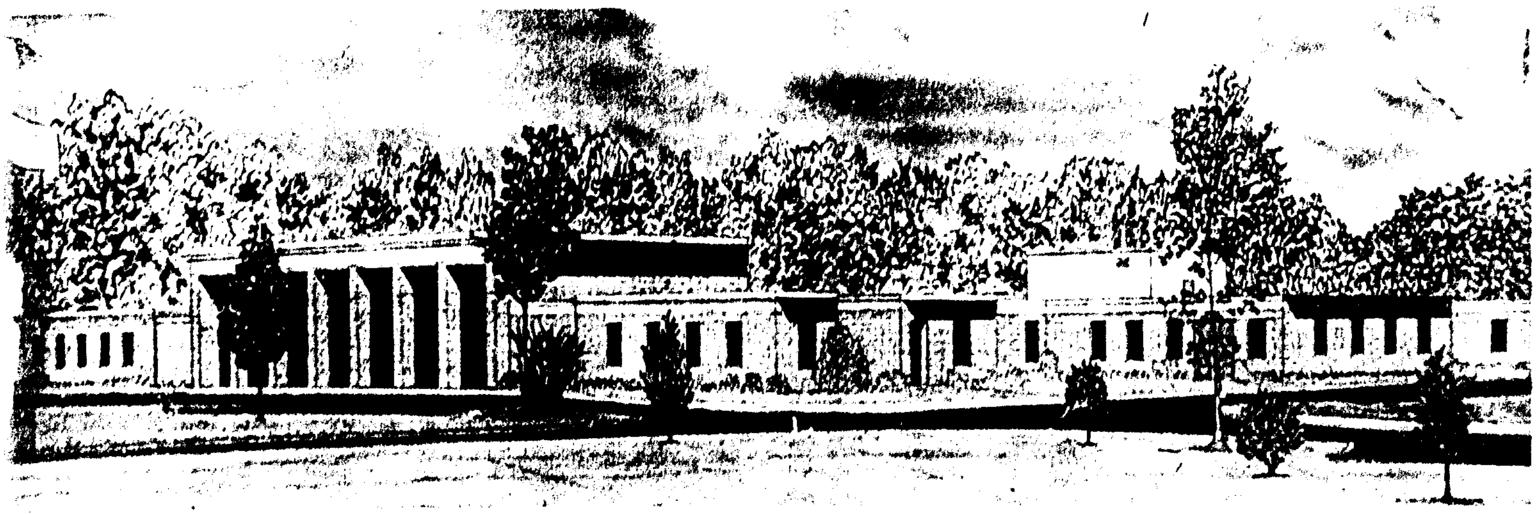
September 1979

Final Report



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Rocky Mountain Arsenal (RMA), located just northeast of Denver, Colorado, since its establishment in 1942, has produced chemical, biological, and incendiary munitions and destroyed chemical munitions. Additionally, private corporations have used leased facilities at the Arsenal for pesticide production. Wastes from these operations have been placed in several basins at RMA.

Discovery of off-post contamination led to Cease and Desist Orders from
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20. ABSTRACT (Continued)

the state of Colorado, which required that off-post contamination by two organic substances cease. As a result of these orders and a continuing program to contain and treat migrating wastes and to identify, isolate, and treat pollution sources contributing to this migration, the Engineering Group, Soil Mechanics Division, Geotechnical Laboratory of WES, was tasked to study one of the waste basins, Basin F.

The principal tasks of the study were to develop the geohydrologic setting in the area of the basin, select feasible containment alternatives, determine the effect of basin wastes on the construction materials of each alternative, recommend one alternative, and provide a conceptual design of the containment system and a monitoring system.

Basin F overlies a sequence of fine-grained alluvial soils underlain by coarser alluvial soils that form the shallow or alluvial aquifer located just above the Denver formation. The Denver formation, consisting of interbedded clay shales, sandstones, lignite, and siltstone, is located at a depth of 20 to 60 ft in the basin area. Groundwater flows in a northwesterly direction beneath the basin at a rate of approximately 44 gpm. Contribution of the basin to groundwater flow is estimated at 1 to 2 gpm.

A barrier containment system consisting of a vertical physical barrier embedded in the Denver formation, gradient control wells, and a monitoring system is proposed. The various alternatives studied include sheet pile, grouting, conventional and thin-wall slurry trench, and synthetic membrane barriers. Compatibility studies were made to determine the effects of the basin waste on the various construction materials of each alternative. The conventional slurry trench was chosen as the best alternative with certain qualifications.

The principal concern with containment of the basin and associated aquifers is possible leakage from the contained area through the sand and sandstone lenses of the Denver formation. It is recommended that this possibility be evaluated and the effect of the barrier on areal groundwater flow be modeled. Projects undertaken since the completion of this study (September 1978) are further defining the characteristics of the Denver formation and its effect on the containment of Basin [illegible] [illegible]dditionally, longer duration compatibility testing is under way.

Evaporation of the liqu[illegible] contents of Basin F, plus placement of a low infiltration, well-drained cover, is recommended to immobilize the wastes in the basin. This will provide high integrity storage of a concentrated waste with a low risk of migration.

PREFACE

The investigation reported herein was conducted during the period from 1 December 1977 to 30 September 1978 by the Geotechnical Laboratory (GL) of the U. S. Army Engineer Waterways Experiment Station (WES) for the Contamination Control Directorate, Rocky Mountain Arsenal (RMA), Commerce City, Colo. Funding for this study was authorized by Intra-Army Order No. RM 56-78, dated 9 November 1977, and Change Order 1 to RM 56-78, dated 12 April 1978.

This report was prepared by Mr. S. P. Miller of the Engineering Group (EG), GL, WES, under the direct supervision of Mr. G. B. Mitchell, Chief, EG, and the general supervision of Mr. C. L. McAnear, Chief, Soil Mechanics Division, and Mr. J. P. Sale, Chief, GL.

Dr. James K. Mitchell, University of California at Berkeley, has provided review of compatibility study plans and the geotechnical findings during the investigation. Compatibility studies reported herein were conducted by D'Appolonia Consulting Engineers, Inc., Pittsburgh, Pa., Structures Laboratory (SL), WES, and Matrecon, Inc., Oakland, Calif.

Special acknowledgment is extended to the following individuals for their assistance and encouragement during the course of this investigation: Dr. B. Michael Arndt and Messrs. Ed Berry, Irvin Glassman, Don Cook, Brian Anderson, and Carl Loven of RMA; and Messrs. Andrew Anderson, Dennis Wynne, James Zarzyki, and Don Campbell, U. S. Army Toxic and Hazardous Materials Agency (USATHMA), Aberdeen Proving Ground, Md.; and Joseph Kolmer, formerly USATHMA.

Commanders and Directors of the WES during the preparation of this report were COL John L. Cannon, CE, and COL Nelson P. Conover, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	4046.856	square metres
feet	0.3048	metres
feet per day	0.3048	metres per day
gallons per minute	0.003785412	cubic metres per minute
gallons per year	0.003785412	cubic metres per year
inches	2.54	centimetres
miles (U. S. statute)	1.609344	kilometres
mils	0.0254	millimetres
parts per million	1.0	millilitres per cubic metre
pounds (force) per square foot	47.88026	pascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square feet	0.09290304	square metres
square miles	2.589988	square kilometres

GEOTECHNICAL CONTAINMENT ALTERNATIVES FOR INDUSTRIAL WASTE BASIN F, ROCKY MOUNTAIN ARSENAL, DENVER, COLORADO; A QUANTITATIVE EVALUATION

PART I: INTRODUCTION

Background

1. Rocky Mountain Arsenal (RMA) covers an area of approximately 27 square miles* northeast of Denver, Colorado, and immediately north of Denver Stapleton International Airport (Figure 1). Since its establishment in 1942, RMA has produced chemical, biological, and incendiary munitions and has demilitarized obsolete chemical munitions. Military operations at RMA have included the production of GB nerve gas, lewisite, mustard gas, arsenic chloride, anticrop agents, and chlorine gas, as well as the fabrication of munitions containing white phosphorus and chemical warfare agents. The demilitarization of GB munitions and mustard-filled munitions and the blending of hydrazine have also been missions of RMA. In addition to these military operations, private corporations have operated and continue to operate industrial facilities for production of pesticides at RMA (Buhts, Malone, and Thompson, 1978, and Kolmer and Anderson, 1977).

2. Industrial waste effluents generated at RMA have been discharged into a basin just north of the original plant area, referred to herein as Basin A. This basin was used for all discharges and was enlarged as greater waste volumes were generated. Further volume increases required the construction of additional basins northwest of Basin A. One of these additional basins, Basin F, is the subject of this report. The basins and other features of RMA are shown in Figure 2.

3. In the summer of 1954, farmers complained that groundwater

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

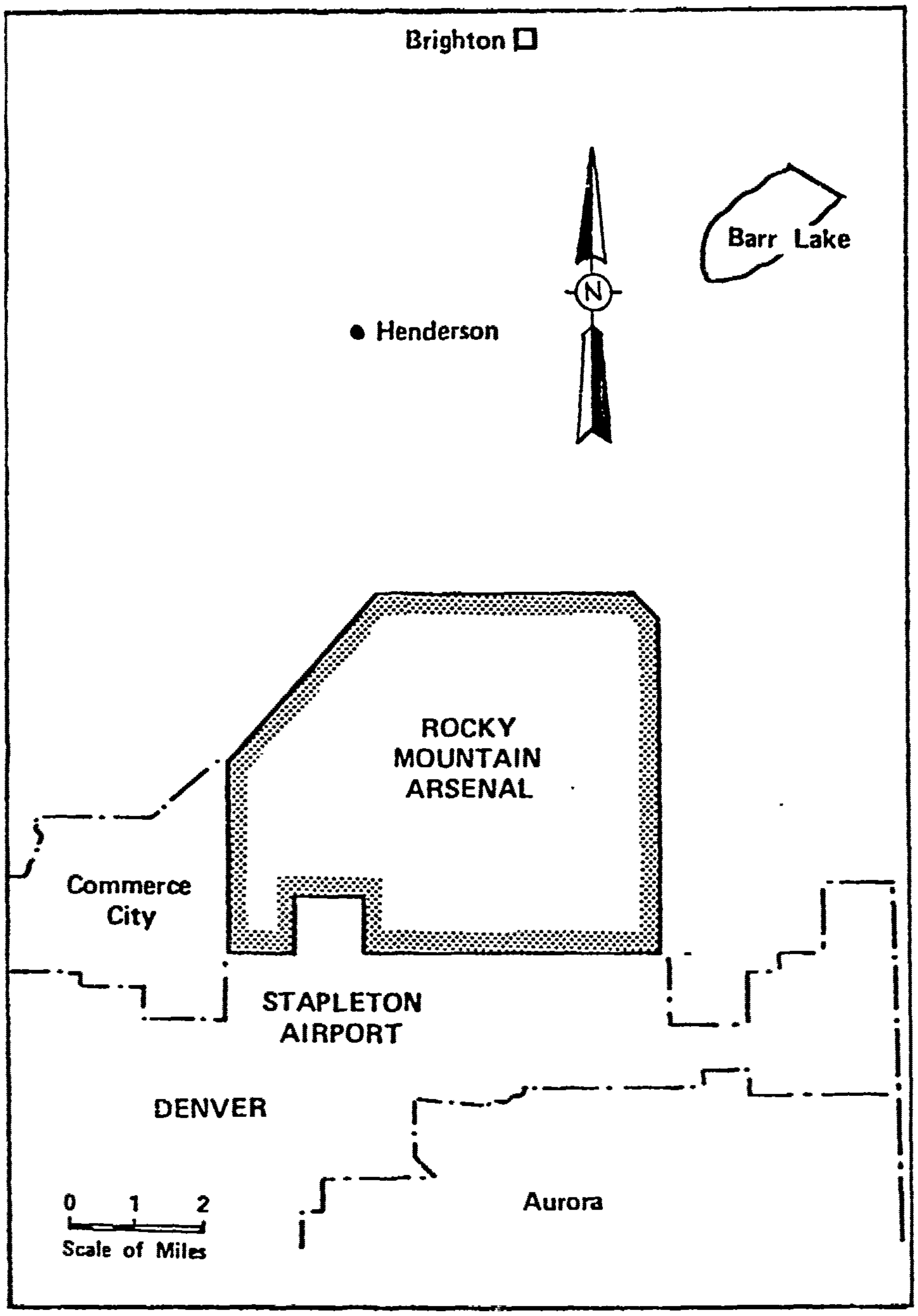


Figure 1. RMA-Denver vicinity (Kolmer and Anderson, 1977)

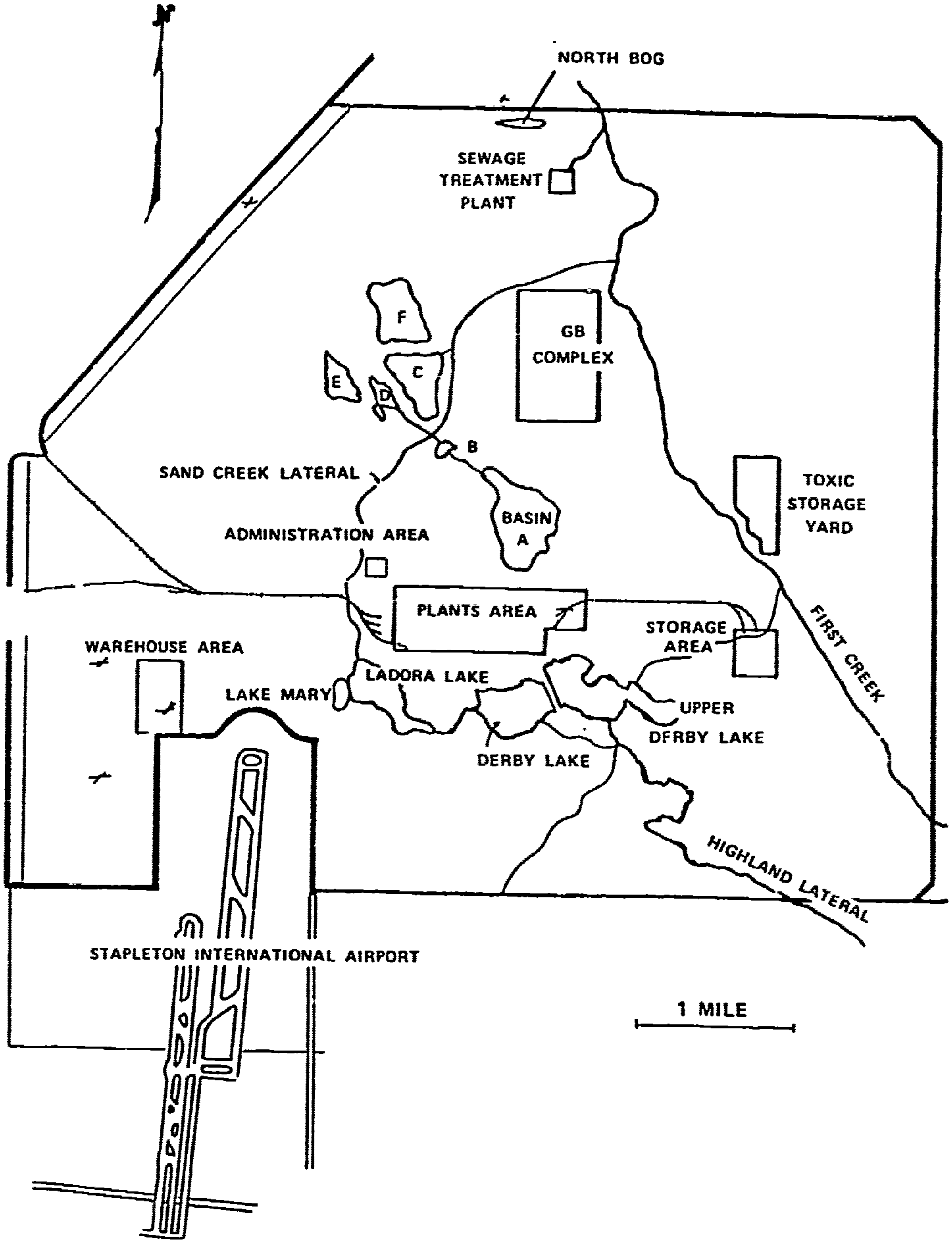


Figure 2. General map of RMA (Kolmer and Anderson, 1977)

used for irrigation near RMA was damaging crops. Subsequent investigations into the cause of this damage prompted the construction of Basin F, which was lined and sealed by laying a catalytic air-blown asphalt membrane over a graded surface and placing a protective 1-ft soil cover over it. After completion in early 1957, Basin F received all industrial wastes generated at RMA. From 1962 to 1966, a 12,045-ft-deep disposal well, adjacent to Basin F, was used to dispose of wastes. In 1966, use of the well was stopped because of earth tremors that occurred in the Denver area during well operations (Kölmer and Anderson, 1977).

4. In 1974, contaminants were detected in surface waters and groundwaters north of RMA. Three Cease and Desist Orders were issued on 7 April 1975 by the Colorado Department of Health. These orders stated that Shell Chemical Company (lessee of part of the RMA plant area for commercial production of various pesticides) and RMA must:

<u>a</u>. Immediately stop the off-post discharge (both surface and subsurface) of DIMP (diisopropylmethylphosphonate, by-product of gas manufacturing and detoxification) and DCPD (dicyclopentadiene, a pesticide by-product).

<u>b</u>. Take action to preclude off-post discharge (both surface and subsurface) of DIMP and DCPD.

<u>c</u>. Provide written notice of compliance with item <u>a</u>.

<u>d</u>. Submit a proposed plan to meet the requirements of item <u>b</u>.

<u>e</u>. Develop and institute a surveillance plan to verify compliance with items <u>a</u> and <u>b</u>.

As a result of the Cease and Desist Orders, as well as the Army's recognition that contamination and contamination migration have resulted from past operations, a program of contamination control was established and placed under the direction of the Project Manager for Chemical Demilitarization and Installation Restoration (PM CDIR) Aberdeen Proving Ground, Maryland, subsequently designated U. S. Army Toxic and Hazardous Materials Agency (USATHMA). The objectives of the control program at RMA were to (a) contain and treat contaminants that were migrating from RMA and (b) identify, isolate, and treat the pollution sources contributing to the migration of contaminants off post (Kolmer and Anderson, 1977).

5. Basin F, located in the northern portion of Section 26, RMA, has been cited as a source of contamination of groundwater in the alluvial aquifer (Timofeeff, 1976).* The most recent data to indicate leakage from Basin F are contained in a report by Arndt (1978) presenting water quality data from the monitoring wells around Basin F. Figures 3 through 5 show with very few exceptions much higher contaminant concentrations in the northern periphery (in the general direction of groundwater flow) than in the southern portions of Basin F. Because of these indications and the potential they represent for damage to the environment, it was decided to evaluate methods of containing Basin F to prevent any further movement of contamination from the immediate vicinity of this basin and the underlying soils down to a relatively impermeable bedrock strata. Dr. O. Rendon,** temporarily assigned to the U. S. Army Engineer Waterways Experiment Station (WES), at the request of PM CDIR conducted a qualitative evaluation of feasible methods for containment/relocation of the contents of Basin F. The Engineering Group (EG), Soil Mechanics Division (SMD), Geotechnical Laboratory (GL), of WES was directed by the Contaminant Control (CC) Directorate of RMA to conduct a quantitative feasibility evaluation for full-depth containment of Basin F, according to the work statement attached to the funding document, Intra-Army Order No. RM 56-78. Essentially, the EG was to:

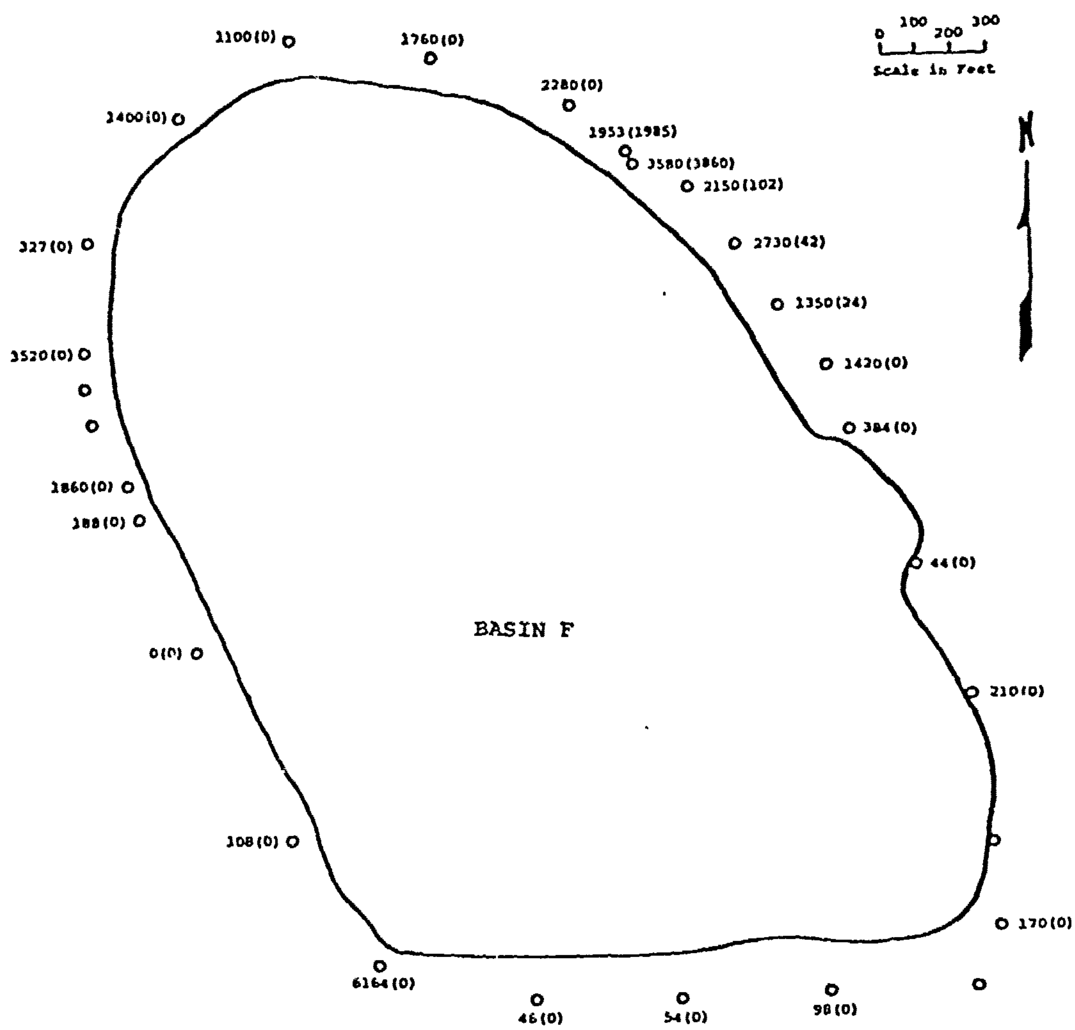
a. Assess the current physical condition of the basin for the determination of need for immediate structural repair.

b. Review past and current material compatibility studies applicable to Basin F, principally to prevent duplication of effort.

c. Develop a program to acquire geotechnical data necessary to select solutions and prepare design criteria. The EG

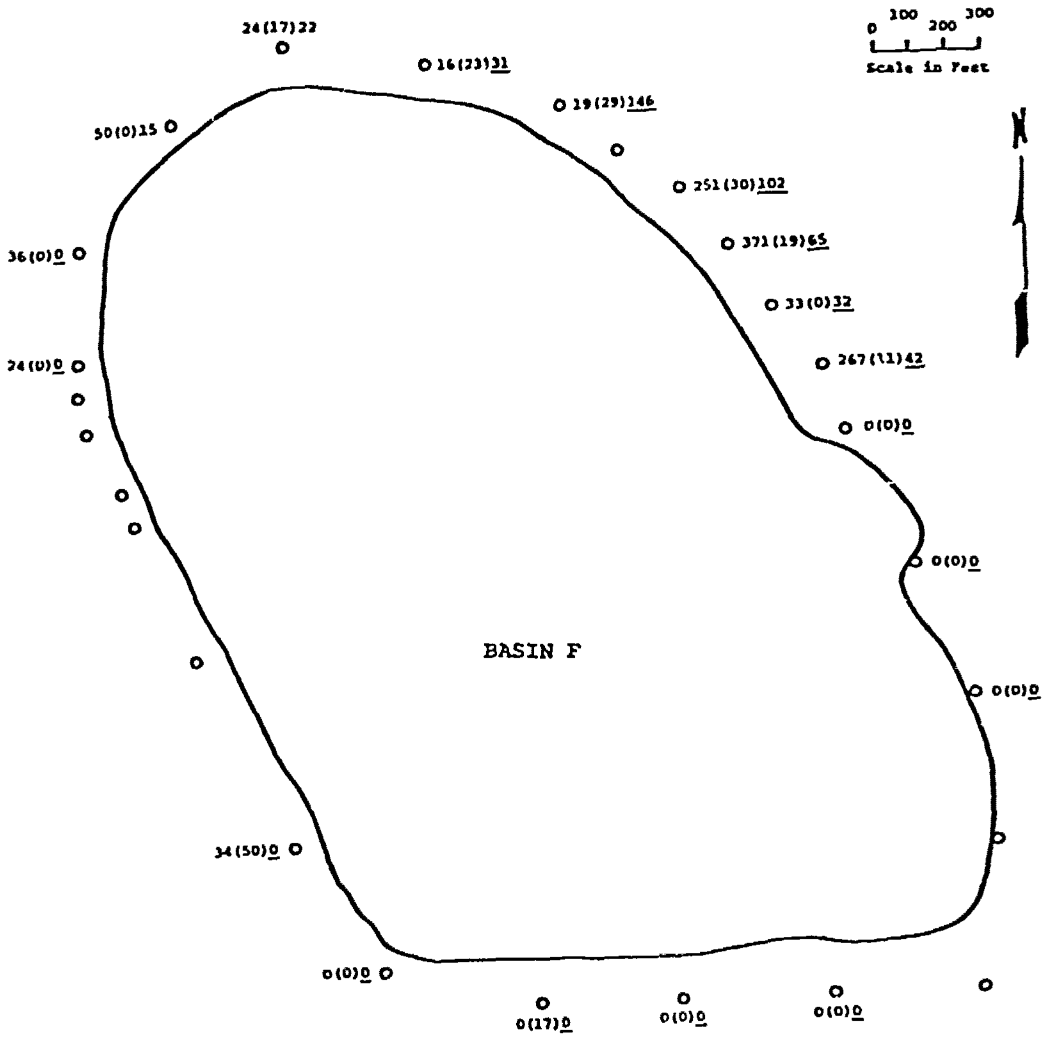
* R. E. Buhts and N. R. Francingues. 1977. "Basin F Investigative Studies (Phase I)" (Draft Report), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

** O. Rendon. 1977. "Containment/Engineered Storage of Basin F Contents, Rocky Mountain Arsenal, Denver, Colorado" (Draft Report), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.



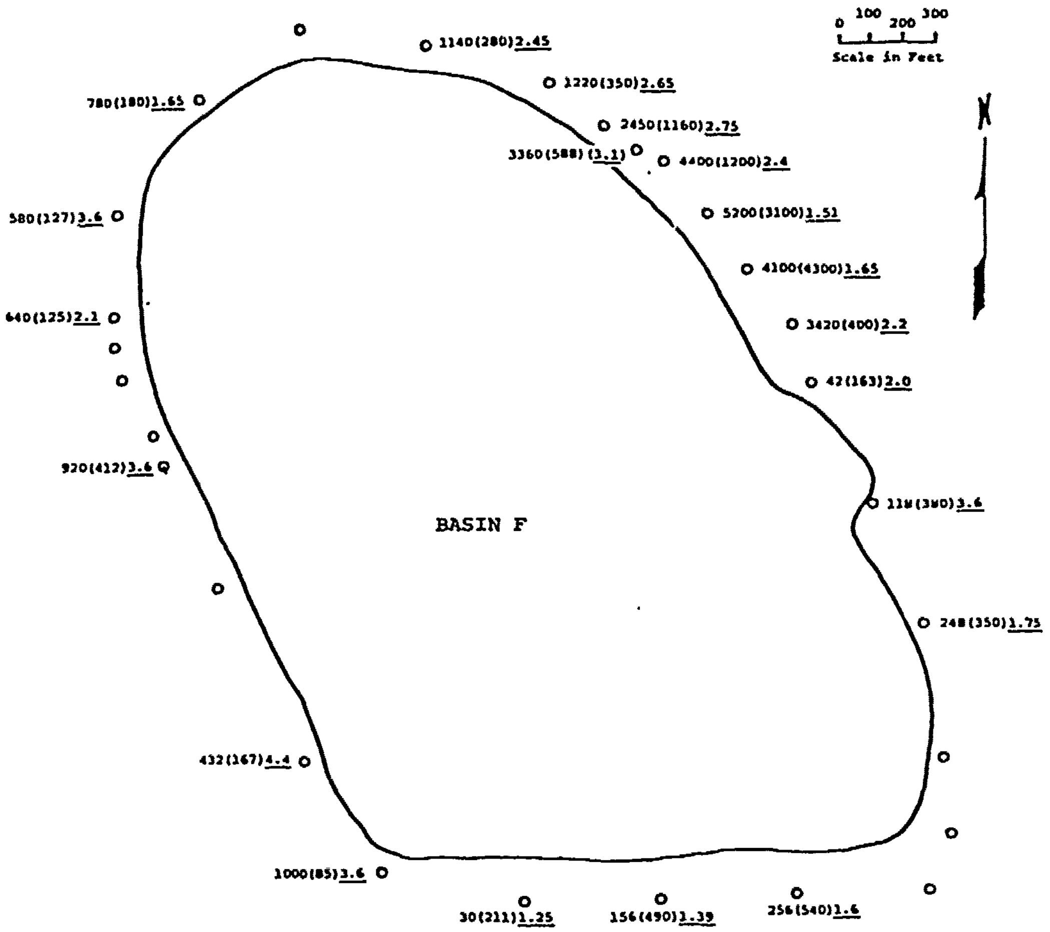
DIMP (DCPD)

Figure 3. Distribution of DIMP and DCPD, ppb (Arndt, 1978)



Sulfoxide (Oxathane) <u>Dithiane</u>

Figure 4. Distribution of organo-sulfur compounds, ppb (Arndt, 1978)



Chloride (Sulfate) Fluoride

Figure 5. Distribution of chloride, sulfate, and fluoride, ppm (Arndt, 1978)

may contract with other WES elements and other Government agencies as necessary for this acquisition.

d. Choose materials and develop a program for performing needed material compatibility studies. The EG may contract with other WES elements, other Government agencies, and/or private industry as necessary to perform these studies.

e. Submit a report with appropriate documentation presenting rationales leading to the selection of the most feasible solutions and describing pertinent design criteria for the recommended solutions.

Subsequent communications with CC, RMA personnel defined containment of Basin F to be surrounding, full depth (to a relatively impermeable continuous strata, if such existed), and in place. Item a was addressed in an interim report, "Dike Stability Analysis, Basin F, Rocky Mountain Arsenal, Denver, Colorado," by G. B. Mitchell and Yu-Shih Jeng, EG, June 1978. Items b and d are presented in Appendix A. Item c was developed in close cooperation with the Geohydrology Division of CC, RMA, particularly Dr. B. M. Arndt and Mr. B. Anderson who supplied much of the boring profile and groundwater data. Additional geohydrologic data have been collected and developed that will refine the data in this report.[*,**] However, time restraints limited this study to the geohydrologic data presented herein. Item e is addressed by this report, which presents selections of containment alternatives and associated criteria based on the data collected to date.

Method of Evaluation

6. The evaluation of containment alternatives requires assumptions, collection and development of geotechnical data, determination of

* D. C. Banks. 1979. "Basin F Containment Hydrogeology Assessment" (Draft Report), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

** F. Bopp III. 1979. "Hydrogeology and Water Quality of Basin A Neck Area, Rocky Mountain Arsenal, Denver, Colorado" (Draft Report), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

the compatibility of various alternative construction materials to waste exposure, and collection of construction cost and time characteristics of each alternative. These data are used to determine the alternative characteristics outlined in Figure 6.

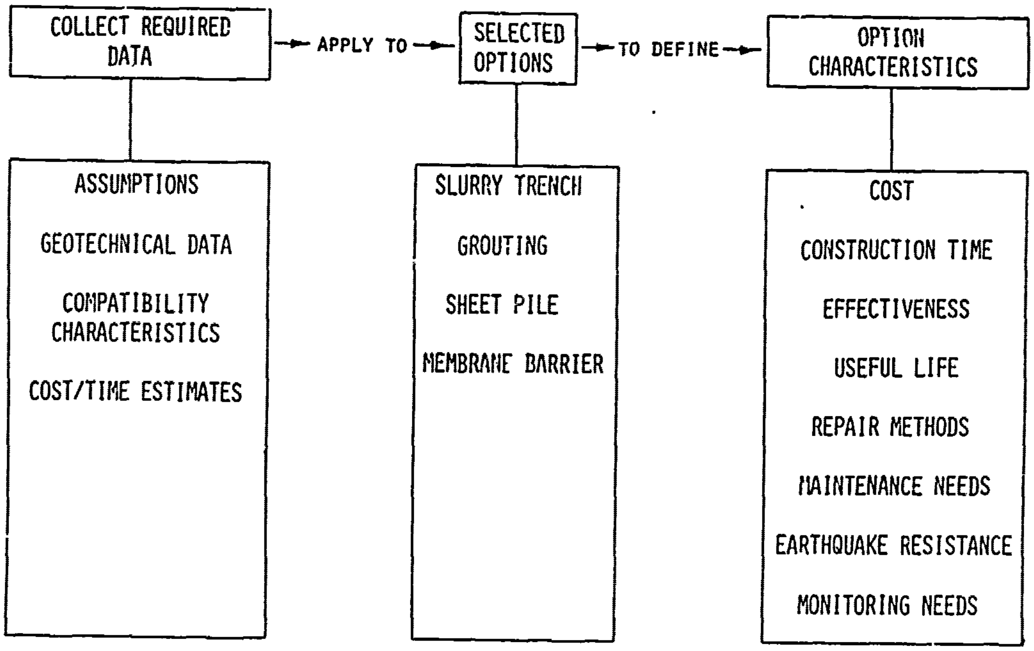


Figure 6. Evaluation method

7. Four basic types of data were used to select and characterize the containment alternatives. Assumptions (in some cases refined as the study progressed) for the study were:

- a. Basin F leaks into the groundwater (the extent and specific location of these leaks and any future leaks are unknown, though sites where waste is coming from beneath the basin may be identified by soil borings and observation wells).
- b. Sewers near Basin F leak (particularly the southeast corner); projects are being designed to eliminate sewer contamination.

c. Flow of groundwater is, in general, to the north.

d. "Bedrock" beneath Basin F is relatively impermeable.

e. Volume for containment purposes is from ground surface to "bedrock" and within an area bounded by a line approximately 50 ft from the toe of the existing dike or basin surface in undiked areas.

Geotechnical data were developed from borings along the periphery and in the general area of Basin F, previous investigations (Arndt, 1978, and U. S. Army Engineer District, Omaha, 1955 and 1961), and soil samples tested at the RMA soils laboratory and the WES soils laboratory. Observation wells installed in several of the borings provided water quality and water level data. Compatibility characteristics of various construction materials were determined by studies described in Appendix A. Cost/time estimates for each alternative are based on current engineering and construction practice and contacts with designers, contractors, and manufacturers.

Barrier Containment Concept

8. The containment of Basin F is based on using a man-made barrier and existing soil and groundwater conditions to isolate, beneath the basin, the alluvial aquifer and, where necessary, deeper aquifers and their associated contaminated groundwater from the areal groundwater system and thus eliminate the basin as a source of pollution by groundwater migration. Basin F and the underlying soils are shown schematically in Figure 7. In general, Basin F is located over fine-grained soils underlain by coarser soils which form the shallow alluvial aquifer that contains the contaminated groundwater. Beneath the aquifer, a stratum of relatively low permeability materials forms what is locally known as "bedrock" and includes shale, siltstone, sandstone, and sandy materials. The sandy material within the "bedrock" or Denver formation may create a problem for achieving the total containment of polluted groundwater. This problem has been addressed in a study just

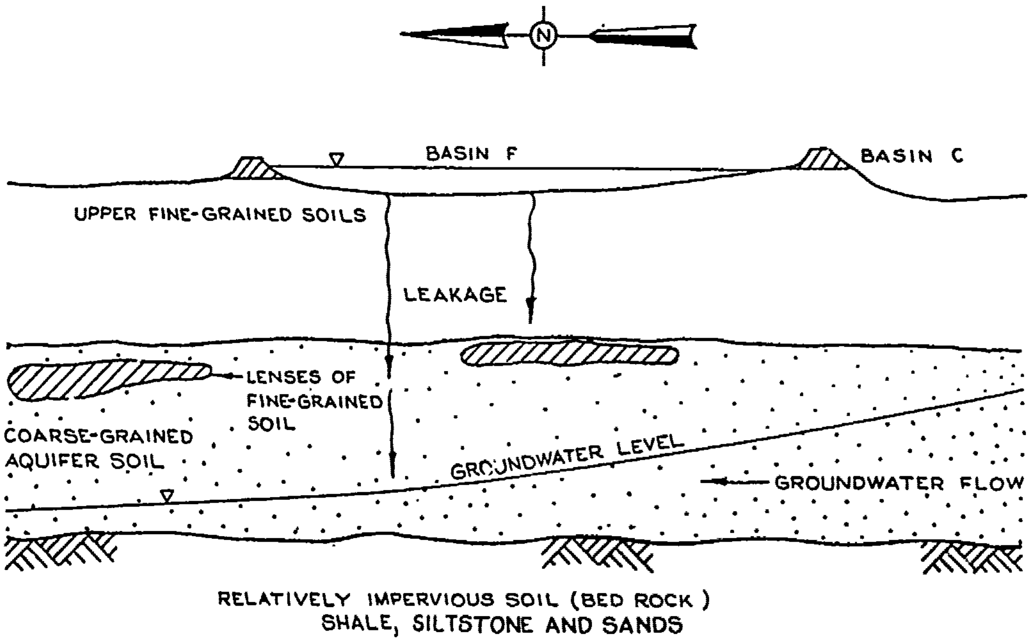


Figure 7. Basin F and underlying soils

completed.* Essentially, some portions of the barrier will have to extend into the Denver formation.

9. A vertical barrier extending from the ground surface down to and connecting to the lower relatively impervious stratum can be used to isolate the contaminated groundwater aquifer(s) beneath Basin F (Figure 8). The barrier should be of low permeability, which can be maintained indefinitely. To increase the effectiveness of the barrier and maintain the isolation, dewatering wells may be used to maintain a shallow gradient into the isolated area. Because groundwater levels beneath Basin F should stabilize (zero gradient) at one level after barrier installation and areal groundwater flow continues south to north, the groundwater levels in the surrounding aquifer should be greater upstream (south) and lower downstream (north) of the barrier than the isolated water level. Thus, wells should be necessary primarily on the

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* Banks, op. cit.

downstream side (in relation to groundwater flow) of the barrier, i.e., on the north side for the schematic shown in Figure 8. This concept would produce a quick and efficient isolation of Basin F as a current contaminant source. The success of this concept depends on the installation of a barrier of high integrity with the ability to maintain this

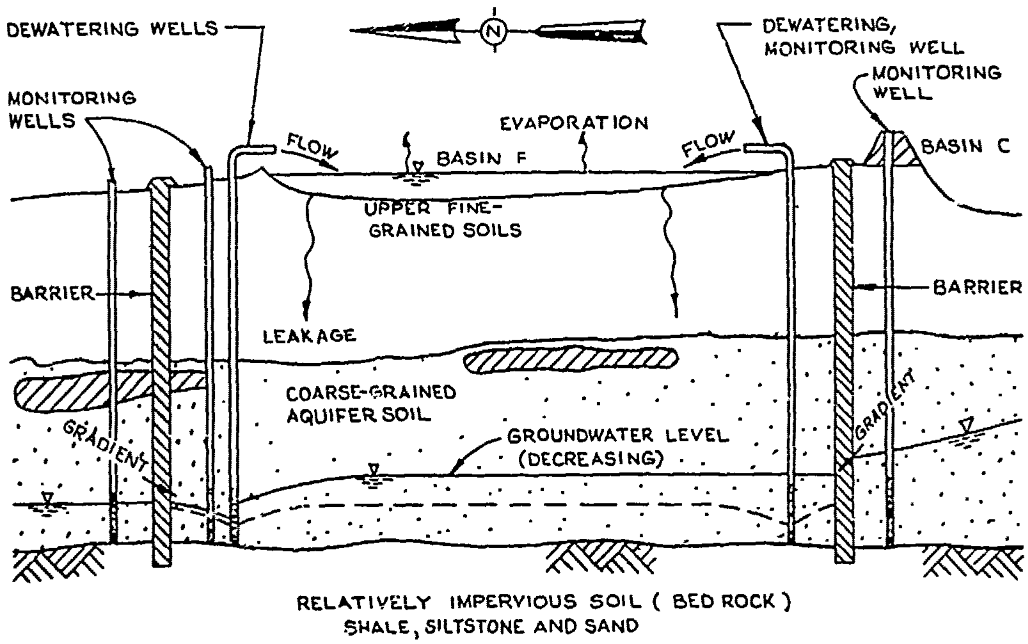

Figure 8. Barrier containment concept, Basin F

integrity against long-term exposure to the contaminated groundwater and the assumption that the lower, relatively impervious strata will prevent contaminant movement beneath the barrier or downward to a possible lower groundwater system that could transport the contaminants.

10. Figures 9 and 10 present a further step toward decreasing the contamination potential of Basin F. Figure 9 shows the reduction in volume of Basin F and the isolated groundwater where Basin F is allowed to evaporate; and Figure 10, the long-term effect of this action and other measures. The dewatering, gradual reduction in area, and covering of dried areas of Basin F with a relatively impermeable cover and the efficient surface drainage to prevent surface water from being a driving force for infiltration of contaminants down to the isolated aquifer will

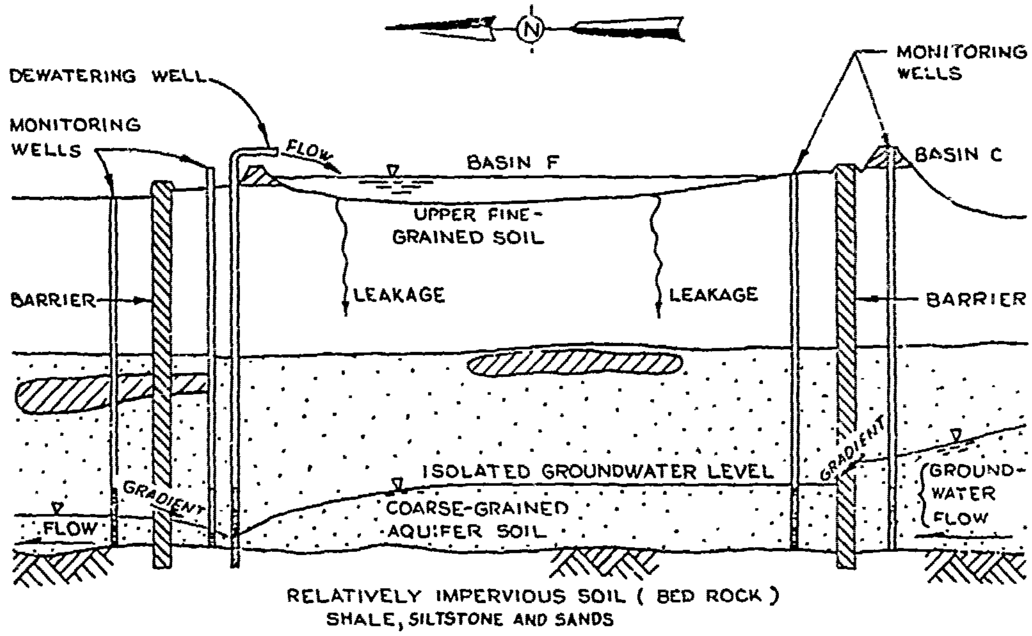

Figure 9. Reduction of potential of Basin F as a contaminant source, intermediate action

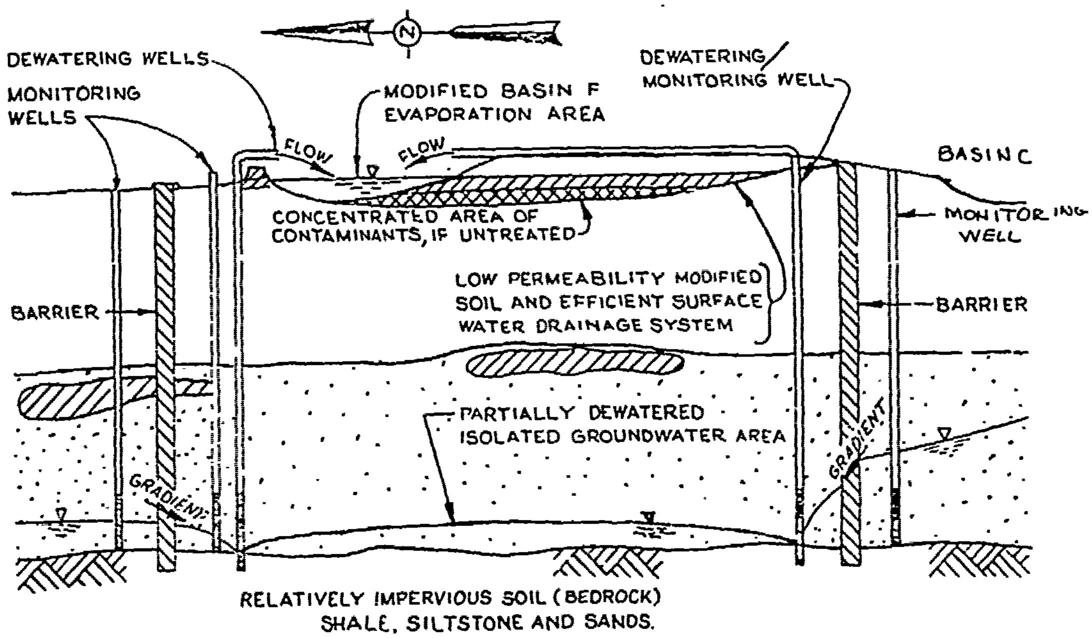

Figure 10. Reduction of potential of Basin F as a contaminant source, long-term status

gradually reduce the potential of this basin to pollute groundwater. If Basin F contaminants are not removed or treated, they will remain in place in a concentrated condition in the near surface soils as a result of surface evaporation and as a residue in the isolated aquifer. These actions will reduce the contamination potential of Basin F to a low level. What is an acceptable level of contamination potential is not defined. It is the objective of this study to evaluate the most reliable means of containing Basin F and thus reduce the contamination potential to a minimum.

PART II: SITE CONDITIONS

Basin F

11. Basin F apparently served as an unlined waste reservoir for an undetermined time prior to the earthwork and asphalt-lining operations of 1956. A 1955 report by the U. S. Army Engineer District, Omaha, showed a reservoir at the approximate location of the present Basin F, though it was smaller and appeared to be diked in two places at the northern end. It was labeled as "a contaminated waste reservoir" (along with reservoirs C, D, and E) by the Omaha District and was cited as a source of groundwater contamination.

12. The 1977 Basin F qualitative containment study* described the construction of Basin F. Essentially formed by diking of low-lying areas with some earthwork cut and fill, Basin F was lined with an asphaltic membrane covered with a 1-ft-thick earth blanket.

Geology

13. The surficial geology of RMA and its environs consists of unconsolidated alluvial terrace deposits and eolian sand of the Quaternary Period. These overlie interbedded clay shales, sandstone, lignite, and siltstone of the Denver formation (Tertiary) termed the Laramie or Dawson formation by De Voto, 1968, and the U. S. Army Engineer District, Omaha, 1961, and underlain by the Cretaceous Arapahoe formation. Apparently, some of the Tertiary deposits made during the time between Cretaceous deposition and the Quaternary alluvium accumulation have been removed by stream erosion, as evidenced in many areas by weathering of the upper surface. Small bedrock outcrops occur on a few of the hills within RMA. Topography is gentle in the area of Basin F with elevations varying from 5170 to 5240 ft with remnants of ancient terraces forming low hills in the area.

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* Rendon, op. cit.

14. De Voto (1968) conducted a detailed study of surficial geology of the RMA area to determine whether the area had experienced Recent fault movement. The study concluded that Recent fault displacements had not been observed in the RMA area.

Groundwater

15. The shallow alluvial aquifer consists primarily of the coarser alluvial soils overlying bedrock, as shown schematically in Figure 7. Groundwater appears to be in the sandy materials above and beneath the bedrock shale, though very little data exist to define the bedrock formations of RMA. The groundwater in the Denver formation at the southeastern corner of Basin F is apparently connected with that in the alluvial aquifer, though the extent of contact between the sandy and silty areas of the bedrock with the alluvial aquifer cannot be determined. (This condition has been addressed in a study just completed).* A deeper aquifer is apparently present in the bedrock, e.g., a 600-ft-deep well was drilled, but not logged, in 1978 just north of RMA to provide a domestic water supply. A U. S. Geological Survey investigation (Robson, 1977) concerning groundwater quality reported the existence of a "deeper" aquifer below an alluvial aquifer, in an area of similar geology from 10 to 15 miles southeast of RMA. This alluvial aquifer was apparently hydraulically connected with groundwater in the upper part of the bedrock though not with the "deeper" bedrock aquifer.

16. It can be assumed that most of the contamination is currently in the upper saturated portion of the alluvial aquifer since many of the bedrock materials are consolidated and fine grained and therefore inhibit vertical and horizontal movement of the groundwater. The possibility exists that some contamination might move through the bedrock beneath the barrier, though movement rates would be slower and volumes much smaller because the materials are finer.

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* Banks, op. cit.

17. Groundwater contours for the shallow aquifer based on 1977-1978 observations are presented in Plate 1. Groundwater levels from observation wells used to construct contours were provided by Dr. B. M. Arndt, RMA. Past groundwater observations (Arndt, 1978; Konikow, 1975; and U. S. Army Engineer District, Omaha, 1961) provide the same general picture of groundwater flow. Insufficient data are available for groundwater flow definition to the east and southeast of Basin F. However, current studies*,** define flow for the alluvial and deeper aquifers in the Basin F area. The groundwater flows beneath the basin in a north-northwesterly direction. From limited groundwater level data in Plate 1, much of the groundwater in areas south and southeast of Basin F (including the Basin A area) apparently moves in a west-northwesterly direction, passing to the south and southwest of Basin F.†

18. Little can be directly determined about the volume Basin F contributes to the groundwater, except it is apparently small. However, an indirect and approximate determination will be presented later.

19. The permeability of the coarser portions of the aquifer beneath Basin F is approximately 200 ft/day. This value is based on a comparison of soil grain sizes (amount of material in aquifer soils passing the No. 200 U. S. standard sieve and the D_{10} size of which 10 percent of the aquifer soil sample is smaller) with those found for aquifer materials at the northern boundary where pump tests indicated a permeability of 210 ft/day.†† The groundwater contours indicate by spacing that the permeability beneath Basin F is comparable with that at the northern boundary (Plate 1). Correlation was also made using D_{10} sizes and a graph developed from experience with Mississippi River Valley sands (Dept. of Army, Navy, and Air Force, 1971). The D_{10} size

* Banks, op.cit.

** Bopp, op.cit.

† R. A. Zebell. 1979. "Study of Alluvial Aquifer, Basin F to the North Boundary, Rocky Mountain Arsensal, Denver, Colorado" (Draft Report), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

†† S. P. Miller. 1976. "Interim Containment System, Groundwater Treatment, Rocky Mountain Arsenal, Denver, Colorado" (Draft Report), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

is approximately 0.15 to 0.20 mm, which indicates a permeability of 200-250 ft/day, though this comparison is more applicable to cleaner sands (less minus 200 sieve material). Some materials in the alluvial aquifer capable of carrying water have lower permeabilities and 10 to 20 percent passing the No. 200 U. S. standard sieve.

Subsurface Investigations

20. Plate 2 presents a plan view of the borings that provide geotechnical definition of Basin F. Borings are numbered in the 400 series, with those cased and used as observation wells having a well number in parentheses prefixed by the number of the land section (26) in which Basin F is located. Borings were made by a hollow stem auger with an outside diameter of 8 in. and an inside diameter of 3-1/8 in. After the initial boring program was completed, an additional six holes (405, 419, 438, 455, 461, and 492) were requested by the WES to penetrate the bedrock for a depth of 20 ft to ascertain the types of soil underlying the alluvium-bedrock contact and obtain blow counts for determination of approximate soil strength values. Split spoon samples were taken at 5-ft increments or change in stratum, with each sample divided between the RMA Geophysical Analysis Laboratory (GAL) and the WES Soils Laboratory. Moisture contents were determined by GAL, and specific gravity, grain size, Atterberg limits, and laboratory classifications were determined by WES. Grain-size curves, laboratory classifications, and field logs for these borings are on file at RMA.

Soil Properties

21. Plate 3 presents the Unified Soil Classification System as the legend for Plates 4 through 7, which show the soil profile around Basin F. Soils for all borings are identified by laboratory classification where such data were available and by field classification otherwise, except borings 405, 419, 438, 455, 461, and 492, which are laboratory classified. These six borings are shown separately with blow

counts (except boring 492), water contents, Atterberg limits, specific gravities, and estimated values of density, strengths, and porosities in Plates 8 through 13. Densities and strengths were estimated from Standard Penetration Test (blow counts) and laboratory test results using previous experience with soils in the local area. Porosities were calculated with unit weight and specific gravity assuming saturation below the groundwater table. The overburden alluvial soils are generally silty sands (SM) underlain by lean clays (CL) that, in turn, are underlain by the alluvial aquifer consisting of poorly and well-graded sands (SP and SW) and silty sand (SM). Beneath the alluvial aquifer materials lies the bedrock material (Denver formation), which is generally first encountered as a weathered shale or mudstone but consists also of weathered sandstone (SM) and siltstone (ML) beneath the shale layer. In some areas (particularly beneath the southeast corner of Basin F), the upper bedrock is an SM. Almost every one of the borings indicates the underlying shale material, though a few borings (438, 461, 468, and 492) exhibit sands or silts beneath the weathered shale. Below about the 40-ft depth in holes 455 and 461, high blow counts (100 blows per foot plus) were recorded.

PART III: CONTAINMENT ALTERNATIVES

Barrier Criteria

22. As previously stated, long-term integrity and low permeability of the barrier are paramount factors in determining barrier effectiveness. These and other properties may be listed as several specific barrier characteristics:

a. Cost.

b. Costruction time.

c. Effectiveness.

d. Useful life.

e. Repair methods.

f. Maintenance needs.

g. Earthquake resistance.

h. Monitoring needs.

Items a, b, c, and d, will be addressed as each type of barrier alternative is considered, and e through h under separate headings. The evaluation of these characteristics for each barrier alternative is based on soil and geologic conditions, current projects, past experience with each method, material properties, and consideration of working in a contaminated environment.

Barrier Alignment

23. Barrier alignment, as located in Plate 14, minimizes the length of the barrier and provides approximately 75 ft of exterior clearance from the diked areas of Basin F. This clearance is a general requirement for trench stability of the slurry trench alternative. The final alignment should be chosen after a survey of utility locations, particularly around the buildings located just northeast of the basin; the location of monitoring system wells should be determined to leave as many existing observation wells as possible; and a study of trench

stability during construction should be made for the slurry trench alternative.

24. The locations of alignment stations and the distances between them are summarized below. The dimensions for the alignment and barrier are approximate and will be determined by final alignment selection and survey. Barrier length will be 8400 ft, with an average depth of 60 ft and maximum depth of 80 ft in the southeast corner of Basin F. Thus, the barrier area will be somewhat greater than 500,000 sq ft.

Station	Colorado State Plane Coordinates		Length Between Stations, ft
	North	East	
A	188254	2181747	
			635
B	188875	2181890	
			605
C	189435	2181665	
			730
D ("on line")	190000	2181215	
			730
E	190576	2180762	
			911
F	190784	2179875	
			746
G	190357	2179264	
			721
H	189636	2179276	
			1593
I	188255	2180016	
			1740
A	188254	2181747	
		Total	8411

25. Barrier key strata are marked on the soil profiles in Plates 4 through 7; as noted on these plates, the barrier should key into these strata a minimum of 2 ft. Actual depth should be determined during excavation by having a competent engineer determine from soil samples or cuttings that the keying strata have been reached.

26. The earthwork will be necessary for the slurry trench alternative to provide a working surface for the equipment to excavate the trench and mix and place the backfill. However, the earthwork can be minimized by smooth shallow grades between areas of different elevations along the alignment. A thorough analysis should be made of the effect

of the embankment between Basins F and C on the stability of the slurry trench during construction. The embankment may require modification or removal. Along the southern periphery of Basin F, barrier construction should begin and proceed northward up the east side of the basin. This will minimize the amount of groundwater retained beneath Basin F interior of the completed barrier.

Interior Dewatering

27. By providing an inward gradient, the dewatering system, which consists of developed dewatering wells, interior to the barrier, enhances the effectiveness of the barrier in two ways. The inward gradient prevents the groundwater from moving out of the containment and also lessens any effect of the contaminated groundwater on the barrier material. The dewatering wells shown in Plate 14 have closer spacing in the northern portion of Basin F periphery since the groundwater level internal to the barrier will need to be reduced more in this area than in the southern periphery to provide an inward gradient as illustrated in Figure 8.

28. An analysis to illustrate the effect of not maintaining a zero or inward gradient to the barrier can be made with the following conservative assumptions:

- a. No attempt made to control gradient across the barrier, e.g., no dewatering wells.
- b. Permeability of the barrier $k = 1 \times 10^{-6}$ cm/sec or 0.0028 ft/day.
- c. Barrier thickness = 5 ft.
- d. Average saturated thickness of aquifer beneath Basin F = 7.5 ft.
- e. Length of barrier where interior groundwater level exceeds exterior groundwater level = 4000 ft.
- f. Exterior groundwater level one half of interior level = 3.75 ft.
- g. Negligible volume added to interior groundwater by Basin F leakage (see leakage computation below).

For these conditions, the flow through the barrier would be from 150,000 to 200,000 gal/year. If Basin F leakage does or will in the future contribute significant volume to the interior groundwater, the seepage rate would increase because of increased interior groundwater level (increases gradient across the barrier) and increased area of flow through the barrier.

29. An estimate can be made of the current leakage from Basin F into the groundwater flow (a maximum of 44 gpm) by evaluating the dilution effects of the groundwater flow beneath Basin F. Assume that:

a. For northwesterly two thirds of Basin F, cross-sectional area of flow = 5 to 7 ft of saturated thickness (average 6 ft).

b. Beneath Basin F, a 2000-ft width of flow; therefore, area of flow = 6 ft × 2000 ft = 12,000 sq ft.

c. For northwesterly two thirds of Basin F, gradient =

$$\frac{\text{head drop}}{\text{length of flow}} = \frac{7\ \text{ft}}{2000\ \text{ft}} = 0.0035$$

d. Permeability = 200 ft/day.

Figures 3, 4, and 5, particularly Figure 5, indicate that approximately the eastern one third of the groundwater flow beneath Basin F has appreciable contamination and that this is approximately a 10 or 15 to 1 dilution of Basin F (using chlorides and sulfates in Figure 5). If one third of the 44 gpm has this dilution, it appears that Basin F contributes from 1 to 2 gpm to the groundwater. This value is also affected by whatever dilution takes place as the Basin F fluid moves downward from the basin to the groundwater.

30. The quality of water passing through a slurry trench barrier will most likely increase. This action has been indicated by a marked increase in color quality of the one-half dilution Basin F fluid after passage through the bentonite specimens used in the bentonite compatibility studies (Appendix A). Dilution effects on the fluid would probably decrease with time as the exchange or retaining capacity of the bentonite is depleted. Plans have been made for a chemical analysis of the discharge fluid from the various test specimens, which will be

compared with the chemical analysis of the one-half dilution Basin F fluid.

31. Wells may be pumped periodically with a portable pump, as needed to maintain a gradient through the barrier toward the interior, decreasing pump exposure to the contaminants. It is proposed that the wells discharge into Basin F. This volume must be considered in any evaporation plan for Basin F contents.

32. The dewatering wells should be located in the deeper and coarser portions of the aquifer to be most efficient. Well screens will be necessary only in lower portions of the aquifer; 5- to 10-ft lengths will be sufficient in most cases. Design and construction should be similar to the dewatering wells installed at the northern boundary. Department of the Army, Navy, and Air Force (1977) and Universal Oil Products, Johnson Division (1966), provide design details and grain-size curves that can be used for screen and gravel pack sizing. Compatibility tests on polyvinyl chloride (PVC) and stainless steel well screen (Appendix A) provide data on deterioration.

33. Dewatering wells may be installed simultaneously with the barrier. Each well will cost approximately $15,000 including materials, installation, and development.

34. As the groundwater levels interior and exterior to the barrier stabilize, the amount of pumping and possible need for additional wells to maintain an inward gradient will become evident from water levels indicated by the monitoring wells.

35. If dewatering of the aquifer interior to the barrier is desired, additional wells will be required to maximize the amount of contained water removed. Because of the relatively low permeability of much of the aquifer and the restriction to placement of wells only around the periphery of Basin F, dewatering the aquifer beneath Basin F to any large degree would be difficult.

Steel Sheet Pile

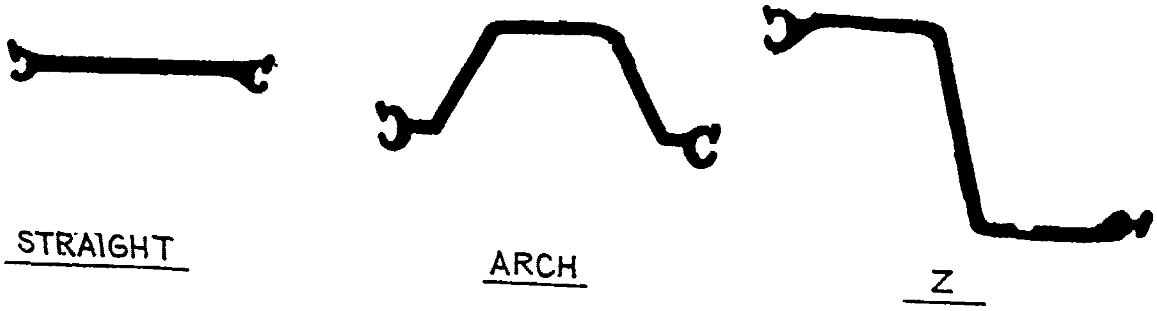
36. Steel sheet piles are used for seepage control in coffer dams

and beneath structures, such as dams and weirs, to give moving groundwater a longer and less open path beneath a structure. This reduces seepage forces acting on the structure, which might cause its movement and failure and prevent erosion of soil by groundwater flow (piping). These objectives do not necessarily require a high degree of flow reduction to be successful. Sheet piles are produced in straight, arch, and Z sections (Figure 11a), in thicknesses normally from 3/8 to 1/2 in., and are joined by interlocks along the edge of each pile to form a continuous wall or barrier (Figure 11b).

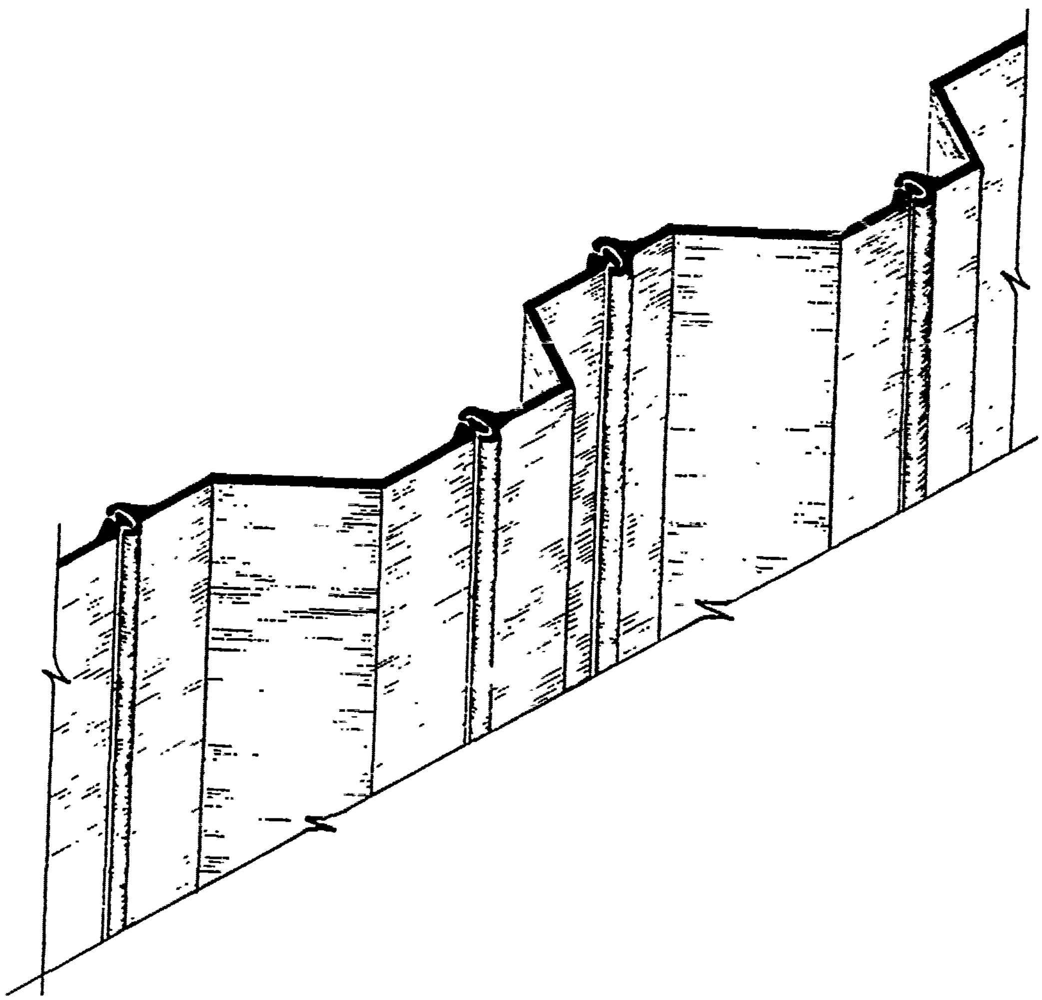
37. Several studies have evaluated the effectiveness of sheet pile to stop groundwater flow, one of the most comprehensive being a report by Greer, Moorhouse, and Millet (1970). This review, based on interviews, a state-of-the-art literature review, and results of project instrumentation to determine the amount of leakage through sheet piles, concluded that sheet pile barriers beneath hydraulic structures are rarely effective as a seepage cutoff. Even the few instrumented studies show the seepage cutoff efficiency of sheet piles to be low.

38. Several methods of sealing the interlocks (where leaks occur) have been tried with varying success. These include coating the interlocks with bentonite before driving (with subsequent swelling of the bentonite with exposure to water after driving) and grouting the interlocks. Grouting is done either after driving through tubes welded to the pile interlock area prior to driving and then grouting, or by driving or jetting the injection pipe along the interlocks of the in-place pile and pumping the grout in as the injection pipe is withdrawn. The bentonite coating method is subject to scraping off during driving and is dependent on a successful bentonite swelling, while the grouting to completely fill the soil voids is questionable and expensive; neither method has been proved to produce a positive cutoff.

39. Other sources of leaks are broken interlocks due to hard driving and failure to seal pile tips into the impervious formation. These problems are particularly hard (or impossible) to identify and locate if the complete installation is underground as would be the case for the containment barrier. Another article (Telling, Menzies, and



a. Sections



b. Interlocking of sections

Figure 11. Sheet pile installation

Simons, 1978) examining the effectiveness of cutoff walls states, "Clearly the overall condition of an installed sheet pile cutoff wall is indeterminate." Another variation reported (U. S. Army Engineer District, Mobile, 1971) is the use of a jetted slurry trench to allow installation of sheet pile with sound interlocks. This method also depends on bentonite to provide the interlock seal.

40. Steel corrodes under normal ground conditions at the rate of 2 to 5 mils/year for the first several years and will generally then decrease (U. S. Steel Corporation, 1975). Saline waters, such as Basin F waste, may accelerate corrosion. Data from a previous study (Handt, 1960) of the effects of Basin F waste on mild steel gave a value of approximately 2 mils/year for unaerated waste and up to 19 mils/year for aerated waste. A sheet pile barrier would be exposed to three subsurface environments: (a) relatively dry soils above the water table, (b) moist or alternately wet and dry soils near the water table, and (c) continuously wet soil beneath the water table. Environment (b) is normally the most corrosive and would probably have a corrosion rate approaching that for aerated waste. Assuming 1/2-in. piling and 15-mils/year corrosion rate, the piling would be breached after 33 years. This figure is conservative since the current groundwater contaminant concentration is much less than that of Basin F used for the compatibility study mentioned above.

41. Other concerns include the drivability of the piles in the denser soils beneath Basin F and the need for the pile tip to penetrate the firmer, weathered bedrock to provide a bottom seal for the vertical barrier. If the dense sand/sandstone is to be penetrated (particularly in the southeast corner of Basin F periphery--borings 455 and 461), special requirements for hammers and pile points may be necessary. Test driving of different sections with a chosen hammer(s) will be necessary to determine the minimum acceptable pile section. The piles should then be pulled to check for damage and alignment.

42. Cost of installation was determined from the experience and contact with several pile contractors of the U. S. Army Engineer District, Vicksburg. Estimates varied from $5 to $12 million and did not

include any treatment measures, such as bentonite or grout, to seal the interlocks. The variation is dependent on the type of steel section to be used, requirements for pile tips, and larger capacity hammers. If piling were used and then an acceptable level of seepage reduction was not achieved, there would be the additional expense of remedial measures such as grouting.

Grouting

43. Grouting, the injection of various materials into the voids of soils to form a seepage cutoff or increase soil strength, is a common engineering practice. It is used for essentially the same objectives as sheet pile in seepage control applications, though it can be used in areas where sheet piles cannot easily be installed such as large-grained soils and rock fractures. Many different fluids are used, including cement, bentonite, silica, and various chemicals, the choice depending primarily on the grain size of the soil to be sealed.

44. The relatively inert silica and chemical grouts should not be greatly affected by the contaminants. In general, the smaller the size of the soil grains, the smaller the voids in the soil and the less predictable and more expensive is grouting. A "rule of thumb" is that soils with more than 10 percent passing the No. 200 U. S. standard sieve or fine sand with a small amount of silt cannot be successfully grouted, i.e., a positive seepage cutoff cannot be produced (Cambefort, 1977, and Herndon and Lenahan, 1976). The grain-size curves and the cross sections (Plates 4 through 7) indicate a large part of the saturated materials above the clay and shale portion of the bedrock have more than 10 percent passing the U. S. No. 200 sieve. Thus, the use of grout for a containment barrier would be questionable. The most promising (and expensive) grout for use with finer grained soils, American Cyanamid Company's AM-9, has recently been removed from use because of the hazardous handling qualities of some of it constituents. Grouting is not a feasible alternative for containment of Basin F.

Slurry Trench

45. The slurry trench method of building a seepage cutoff uses a bentonite slurry (essentially drilling mud) to hold a trench open during excavation to a tie-in, such as the low-permeability soil strata, or to a prescribed depth. When used as a cutoff, the trench is normally backfilled with a specified soil mixed with bentonite slurry or a cement bentonite mixture. Initially used as a groundwater control measure for levees, dams, and excavations for foundations below the water table, slurry trenches have more recently been used as a tool to limit contaminant movement by groundwater flow.

46. Generally, the advantages of slurry trenches over other types of groundwater barriers are lower cost, continuous excavation to tie in strata with no need for interlocks (as with sheet pile) or estimation of overlap (grout), and physical evidence (by sampling excavation cuttings) that the barrier extends to the desired strata. The slurry trench, properly constructed, provides a continuous low-permeability (10^{-6} to 10^{-8} cm/sec) barrier confidently tied into the desired soil strata with an indefinite life under normal conditions.

47. Slurry used in slurry trenches is produced by the ability of the montmorillonite clay particles to attract large amounts of water compared with their weight. This property can be affected by brine solutions such as found in Basin F and the groundwater beneath the basin. Compatibility testing, reported in Appendix A, was designed to determine the effects of Basin F polluted groundwater on various materials including bentonite and, if detrimental, what steps may be taken to remedy undesirable effects. Short-term tests conducted by the Structures Laboratory, WES, and results of tests conducted by D'Appolonia Consulting Engineers, Inc. (1978) indicate that Basin F fluid, for the period tested, has little effect on the ability of bentonite to maintain low permeability in soil-bentonite and cement-bentonite mixtures such as would be used as permanent backfill in the slurry trench.

48. Though effects on permanent backfill material appear minimal, a problem may exist in the effect of Basin F groundwater on the bentonite

slurry used to hold the trench open during and after excavation, prior to backfilling. Bentonite slurries can be affected by brines, e.g. seawater, which may inhibit hydration (bentonite clay attracting and holding water) and cause flocculation and subsequent "settling out" of clay from the clay water slurry. Settling would reduce the density of the slurry, which provides stability for the open trench until backfilling. The Structures Laboratory tests indicated that increasing exposure to Basin F fluid causes a thickening of the slurry and an increase in viscosity. The thickening appeared to be a gelling to form a coagulation that did not floc and settle out. Though there was no appreciable decrease in density of the slurry or settling of the bentonite with the injection of increasing amounts of Basin F fluid and the increase in viscosity appeared to have stopped, further study by modeling field conditions should be made.

49. Actual field conditions should be less severe than the laboratory test conditions were since the slurry will move from the trench outward into the aquifer (though only slightly) because of the higher hydrostatic head on the slurry (thus reducing exposure of the slurry to contaminants) and since straight Basin F fluid was used in the laboratory test while the groundwater in the vicinity of Basin F has much lower levels of contaminants than Basin F fluid. Even with these indications, the stability of the open trench is so critical to the successful completion of a slurry trench barrier that additional simple laboratory testing is necessary and should be included in an extended bentonite study.

50. Should there be a problem, development of remedial measures should be required as part of the study. Attapulgite clay, ferrochrome lignosulphonate and other additives have been used in brine environments (Boyes, 1975, and Harza Engineering Company, 1965). Short-term tests should be sufficient since the straight slurry is only temporarily exposed to the groundwater during construction between excavation and backfilling.

51. If the slurry thickens in the open trench, excavation equipment may be inhibited and the use of slurry from the trench for mixing

with the backfill and placement in the trench may be precluded. Fresh bentonite slurry can be used for mixing with the backfill, but excavation equipment should not be retarded by excessively thick slurry in the open trench.

52. Construction control of the lower portions of the slurry trench during excavation and backfilling is particularly important. During construction, careful monitoring should assure that:

- a. The excavation is made into the lower low-permeability strata by observation of cuttings and sampling of the trench bottom.
- b. The trench remains open until backfilled, i.e., there is no buildup of sand cuttings on the bottom of the trench prior to backfilling, and portions of the trench sides have not fallen to the bottom of the trench. This can be ascertained by soundings of the trench depth and sampling of the trench bottom just prior to backfilling.

53. The installation of a slurry trench barrier may be complicated by the deeper, apparently high density or cemented silty sand and shale located in the southeastern periphery of Basin F (shown by borings 455, 458, 461, and 492). Blow counts in borings 455 and 461, which may be abnormally great in silty sands (Terzaghi and Peck, 1967), indicate high densities (100+ blows per foot) in the saturated materials below the 40-ft depth. These materials will probably be hard to excavate. An additional test boring or two in this area during the project design phase could be used to determine difficulty of excavation.

54. It is recommended that a 5-ft-wide trench be used to maximize the resistance to flow, i.e., a longer flow path through the barrier, and provide maximum insurance of barrier integrity. The trench should extend through the alluvial aquifer materials and bedrock pervious soils and have a 2-ft penetration into the underlying low-permeability strata. Good quality water that meets the normal requirements for bentonite slurry must be made available for mixing. General water quality requirements are: pH 7 ± 1, hardness less than 500 ppm, and oil, organics, or other deleterious substances limited to 50 ppm each.

55. Slurry trench cost is normally given in dollars per square foot of cutoff and recently has ranged from $4 to $7 per square foot. The cost of construction around Basin F will exceed normal costs because of the precautions necessary in the contaminated environment and the possibility of requiring a special soil mixture for backfill. The area (505,000 sq ft), multiplied by a basic slurry trench cost of $7 per square foot and then by a factor of 1.3 to allow for construction in a contaminated environment and the possible need for heavier excavation equipment in the southeast portion of the alignment, calculates to slightly more than $4.5 million.

56. Construction time is dependent on the amount of equipment the contractor uses on the job and the time limits set by the contract. Normal slurry trench construction rates for this depth of trench vary from 25 to 100 linear ft/day. Allowing time for earthwork to provide a minimum working surface and mobilization and demobilization, the total time may vary from four months to one year. One year is probably more realistic since a faster construction rate would require duplicate equipment and manning and would result in higher unit costs.

57. Provisions must be made for disposal of materials from the trench excavation if not used for backfill. The contaminated soils might be disposed of in existing contaminated areas of Basin A not subject to leaching into the groundwater system or as filler for Basin F if they could be incorporated into an accelerated evaporation plan. The longer bentonite compatibility study may also indicate that portions of the excavated material can be used for backfill.

58. Consideration was given to thin-wall slurry trench methods. These use a vibrated pile fitted with cement bentonite grout lines, which penetrates to the proper strata and is then withdrawn leaving a thin (1 to 3 in.) cement bentonite wall. This method has not been proven to the depths required around Basin F and depends on the pile to repeatedly align itself with the previous penetration. It is not considered a reliable method for containment of Basin F.

Membrane Barrier

59. Consideration has been given to using a synthetic liner or membrane as a vertical underground barrier. This type of installation has been used at shallow depths near landfills between the ground surface and the top of the water table to provide a vertical barrier to gas movement. Documented experience with membranes as vertical barriers to groundwater movement could not be found, though one company (Schlegel Corporation, 1977) stated in its brochure that this had been done in Europe.

60. Construction of this type of barrier for Basin F containment presents several problems. The most apparent are:

a. Lack of construction experience.

b. Handling and joining large sheets.

c. Stability of trench (probably would need to be installed in a slurry trench excavation).

d. Sealing bottom of membrane to bedrock (grouting, etc.).

e. Custom cutting of sheets to fit varying depths of barrier required.

Installation of the membrane to depths required would include the construction of a slurry trench and backfilling in addition to the cost of membrane and its installation. Because of these problems, a membrane barrier is not considered feasible.

Repair Methods and Maintenance Needs

61. Should leakage through the barrier be indicated by the monitoring system or other means, certain steps should be taken to define the leakage and repair the barrier. If a general area of leakage is discovered, the source must be identified as accurately as possible to minimize the extent of remedial measures required. The most likely method of defining the source is the installation of additional observation wells along the area of suspected leakage. After the leakage area has been specified as accurately as possible, construction to

contain the leakage can be planned and executed.

62. The simplest remedial measure is the installation of a dewatering well on the interior of the barrier adjacent to the leaking area and then pumping the well to maintain an inward flow through the leaking area. The effectiveness of this measure will depend on the size of the leaking area, the quantity and quality of escaping water, and provisions made to handle the water discharged from the well.

63. Leakage may also be contained by the construction of a second remedial barrier that is exterior to the leaking area and tied at each end to the existing barrier at points beyond the leaking area. This remedial barrier should be of the same material as the existing barrier provided the leakage is due to lack of physical continuity of the barrier and not deterioration of the barrier material. The use of materials other than that of the existing barrier may not be satisfactory. For example, the use of grouting as a remedial measure for a slurry trench would present problems with tieing in to the original barrier, i.e., the grout near the tie-in areas would tend to displace into the slurry trench and not into the natural soil because of the low shear strength of the slurry trench. Other choices for remedial barriers are subject to the same disadvantages explained under containment alternatives. Remedial measures for a leaking dewatering slurry trench have recently been used by the U. S. Army Engineer District, Vicksburg. After considering several measures, such as sheet pile and grouting, a parallel slurry trench panel tied to the existing slurry trench was chosen and installed in September 1978. It has since performed successfully.

64. Maintenance requirements for the barrier alternatives are negligible in normal environments. Any maintenance would involve repair of a physical break of the barrier or barrier deterioration due to contaminant attack. As determined by compatibility testing, this possibility is remote.

Earthquake Resistance

65. Since all barrier alternatives would be placed underground and directly in contact with in-place soils, earthquake effects on the barrier should be minimal with energy waves passing through the barrier with little or no displacement relative to the in-place soil. The state of Colorado is located in what is known as seismic zone 1 in which only minor damage is expected (Dept. of the Army, Office of Chief of Engineers, 1977). As stated in the geologic description of RMA, no surface faulting is evident in the vicinity of RMA. Because of its relative thickness (3 to 5 ft) and plasticity, a soil bentonite slurry trench would be less affected by displacements than, and thus be superior to, grout, piling, or a thin-wall slurry trench.

Monitoring Needs

66. The monitoring objectives are (a) reliable detection of contaminated groundwater movement from the contained volume of soil and water beneath Basin F and (b) groundwater gradient data for operation of the dewatering wells in the barrier interior. The design of the monitoring system must consider groundwater flow and barrier effects on flow, location of existing observation wells and barrier construction effects on these wells, and location of dewatering wells.

67. The proposed barrier alignment will remove some existing observation wells, particularly along the east and northeast periphery of Basin F. In general, existing wells along the northwest and west periphery will be inside the barrier, while those along the south side of the basin will be outside the barrier. Plate 14 shows a plan of the barrier alignment, monitoring, and dewatering system. The alignment and consequently the monitoring and dewatering systems will be affected by the barrier location surveys made during the project design phase.

68. The interior wells will be used primarily to ensure that a groundwater gradient is maintained into the barrier. They should also indicat if the expected increase in contaminant concentration in the

contained groundwater occurs as expected once the barrier is complete and Basin F leakage continues. The exterior monitoring wells will determine if a groundwater gradient is being maintained into the contained area and will be the means of detecting any leaks in the barrier system.

69. The new wells used for monitoring (numbered with an M prefix in Plate 14) should be similar to the existing observation wells. The new observation wells should be carefully installed and backfilled around the casing with materials appropriate to each soil stratum penetrated to prevent caving along the sides of the screen and riser pipe. Care should also be taken to prevent cross contamination of different aquifers. It is estimated that 20 wells will be required at $3000 each.

70. Existing wells used in the postconstruction monitoring system will be dependent on the final construction alignment and well survival during construction. The final barrier alignment should be established to retain a maximum number of existing observation wells since they provide the most accurate data base to reference future groundwater quality and level changes. Existing wells should be marked for easy identification during construction, and provisions made in the construction specifications for their protection (e.g., contractor is required to replace any destroyed wells and install posts and concrete pads to protect existing and new wells).

71. The monitoring well screens should be designed using appropriate grain sizes for the aquifer. PVC or stainless steel riser pipe and well screens should be used to extend the life of the wells. Compatibility tests that are in progress on these two types of well screens will provide data on deterioration. The well design presented in TM 5-818-5 (Dept. of Army, Navy, and Air Force, 1971) and by Universal Oil Products, Johnson Division (1966), can be used. Detailed explanations of the groundwater monitoring system operation are provided by Everett et al. (1976), Fenn et al. (1977), and Todd et al. (1976). The possibility of existing or future contamination at levels beneath the alluvial aquifer should be considered. There is essentially no data on any "lower" groundwater flow (e.g., aquifer dimensions, direction of flow, gradient, and flow volume) on which to base a monitoring system.

However, current studies[*,**] provide a definition of Denver formation aquifer characteristics.

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* Banks, op. cit.
** Bopp, op. cit.

PART IV: ADDITIONAL CONSIDERATIONS

Areal Groundwater Flow

72. The effect of isolating approximately 100 acres of the alluvial and upper Denver aquifers beneath Basin F must be considered. The groundwater map indicates that flow beneath Basin F is northwesterly along the basin's longitudinal axis. Barrier installation will cause a shift of current groundwater flow coming from southeast of Basin F to a more westerly direction south of the basin and in a more northerly direction east of the basin. The primary effect would be the western shift since the eastern periphery of Basin F and the proposed alignment are generally parallel to existing groundwater flow east of the basin. This shift will probably cause a decrease in flow north from Basin F toward the northern RMA boundary. A maximum of 44 gpm currently passes beneath Basin F as previously calculated. Some of this blocked flow will continue north around the barrier, and a portion will probably be diverted westward from south of Basin F. The effect of a barrier on groundwater flow can best be analyzed by areal groundwater modeling.

Hydrological Barrier

73. An additional type of containment discussed by personnel of the RMA and WES was a hydrological barrier to the groundwater flow from the Basin F area using dewatering wells with recharge wells and/or partial barriers. Dewatering wells would be located upstream of the groundwater flow into the Basin F area, and recharge wells or barriers downstream of the Basin F area to effect a zero gradient or stagnation of the groundwater beneath the basin. This form of containment is not considered feasible within the constraints of this investigation for the following reasons:

- a. Many wells would be required to ensure a high degree of interception of the groundwater moving beneath Basin F since wells could only be located outside the physical

boundary of the basin and the extent of their influence would be limited by the low permeability of much of the saturated materials.

b. There would be continous operation and maintenance requirements for the wells as long as containment of the groundwater was required.

c. Water removed by the wells would present a problem of storage and/or treatment.

Reduction of Contamination Potential

74. Though not strictly within the scope of this investigation, the evaporation of Basin F liquid should be considered as a very effective measure to reduce the potential of contaminant movement from the basin. The driving force for contaminant movement from Basin F is fluid flow. (Basin F is a fluid and is exposed to precipitation). If the contaminants are deprived of this medium of transport, Basin F waste would be stationary. This state can be approached by the evaporation of as much of the liquid portion of Basin F waste as possible and removal of the influence of precipitation. Several factors influence the rate of fluid decrease. Provided there is no man-made input into Basin F, these factors are:

a. Rate of precipitation.

b. Rate of evaporation.

c. Amount of groundwater discharged from dewatering wells into the basin to maintain the inward gradient.

d. Surface area of the basin used for evaporation.

e. Whether or not the groundwater beneath the basin is removed by dewatering.

75. The evaporation of Basin F has been considered in three previous studies, one of which was not documented but its results were recorded (Mastroianni and Asselin, 1977). Essentially, it has been determined by computer simulation that without waste input to Basin F, it would approach a dry condition in three to seven years. Evaporation is

worthy of further study. The volumes considered for evaporation and/or treatment would be dependent on whether or not the aquifer beneath Basin F is dewatered. Once the liquid has been evaporated, the basin should be covered with a low permeability soil or modified soil and efficient surface drainage provided to remove infiltration of precipitation as a driving force to move the remaining residue downward toward the groundwater.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

76. This study evaluated various containment alternatives for industrial waste Basin F, considering geohydrological and pollutant source characteristics of the basin. A bentonite slurry trench along the alignment shown in Plate 14 with interior dewatering wells and monitoring wells is the best alternative for containing horizontal groundwater flow in the aquifers beneath Basin F. The slurry trench will be the best performer for positive groundwater control, and compatibility studies indicate that Basin F groundwater would have little if any effect on a soil bentonite backfilled slurry trench. To minimize the amount of groundwater captured by constructing a barrier, the completed barrier should extend across the southern periphery of the basin and then proceed northerly up the east side. The barrier should be keyed a minimum of 2 ft into the lower low-permeability strata as shown in Plates 4 through 7.

77. Cost estimates (1978 dollars) for the major components of a slurry trench barrier containment are:

- a. Slurry trench--$4.5 million.
- b. Dewatering wells--$105,000 (seven wells at $15,000 each).
- c. Monitoring wells--$60,000 (20 wells at $3,000 each).

Additional cost considerations include:

- a. Energy costs for dewatering wells.
- b. Manpower for sampling and measuring of monitoring wells.
- c. Possible cost of groundwater diversion if needed due to effects of the barrier on areal groundwater flow.
- d. Possible cost of dewatering well(s) and deeper barrier if necessary to prevent movement of contained water in Denver formation sands.

78. Basin F leakage currently contributes approximately from 1 to 2 gpm to groundwater flow.

79. There are two primary and related problems associated with the barrier containment concept:

a. The connection between the alluvial aquifer and water-bearing strata of the bedrock materials has not and probably cannot easily be defined. This is a characteristic of the geology of RMA and as such applies to any waste containment plan used at RMA.

b. There may be problems constructing a barrier to a low-permeability strata along the southeastern periphery of Basin F, which will require the use of heavier than normal equipment for excavation. Possible problems may occur because of the high blow counts in this area, which indicate high-density materials and/or cementation.

80. The contamination potential may be minimized by slurry trench containment, dewatering of the alluvial aquifer beneath Basin F, evaporation of the fluid portion of Basin F, and application of a low infiltration, efficiently drained cover over the basin area. This action, of course, does not remove the waste or treat it but does provide for high-integrity storage of a concentrated waste with a minimum risk of contamination.

Recommendations

81. Aquifers beneath the alluvial aquifer should be monitored for contamination. The potential for movement downward from the alluvium exists because of limited evidence (lower portions of borings 438 and 468) of the presence of permeable sands. The Denver formation should be explored to determine the impact of any Denver sands on the containment concept. Studies*,** initiated during the final portion of the study are addressing this need.

82. Longer duration compatibility testing should be done. Studies

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* Banks, op. cit.

** Bopp, op. cit.

(estimated duration, 18 months) are being continued beyond those reported by D'Appolonia Consulting Engineers, Inc. (1978), and results will be reported when they are complete.

83. For substantial dewatering of the contained area, additional dewatering wells will be needed, and an analysis of the dewatering should be made.

84. A detailed study using modeling techniques, such as computer modeling, should be made to determine the effect of the barrier and any other structures installed in the aquifer(s) on the areal groundwater flow.

85. Prequalification of slurry trench bidders is highly recommended because of the size of the trench, necessity for high-quality construction, particularly in the lower portions of the trench, and possible excavation difficulties that may be more easily overcome by experienced contractors. Close control of pure slurry density in the open trench should be maintained, particularly in areas of higher groundwater contamination. The stability of the open slurry trench during construction, particularly in the areas of embankments on the north and south ends of Basin F, should be further analyzed.

86. One or two borings should be made in the areas of high blow counts specifically to ascertain how difficult it will be to excavate in these areas.

87. Prior to final location of barrier alignment an accurate survey of Basin F and the surrounding area, including topography, should be made so that all natural features and installations can be accurately located with respect to one another. Some discrepancies have been noted between the different maps and plans of the Basin F area.

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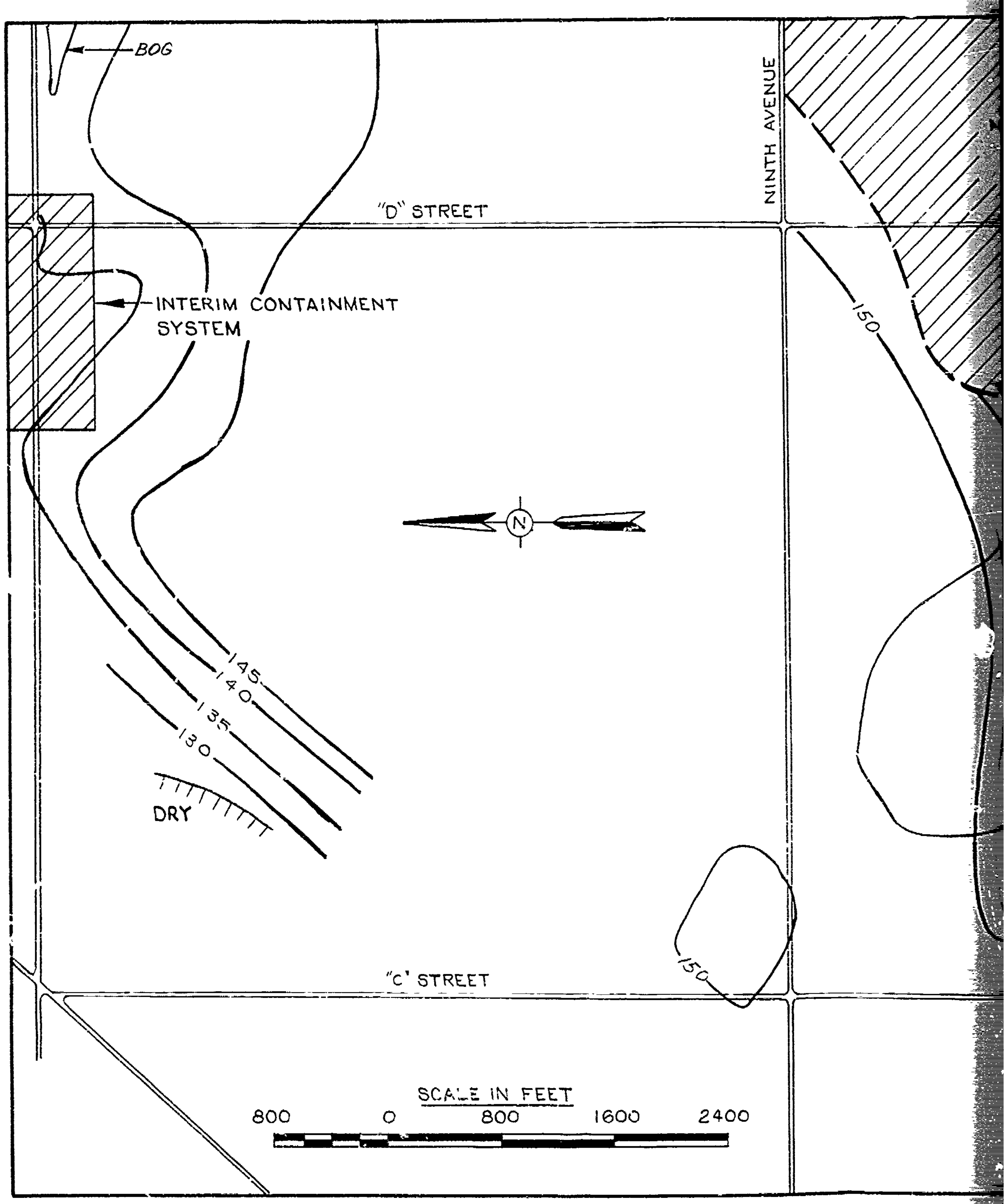
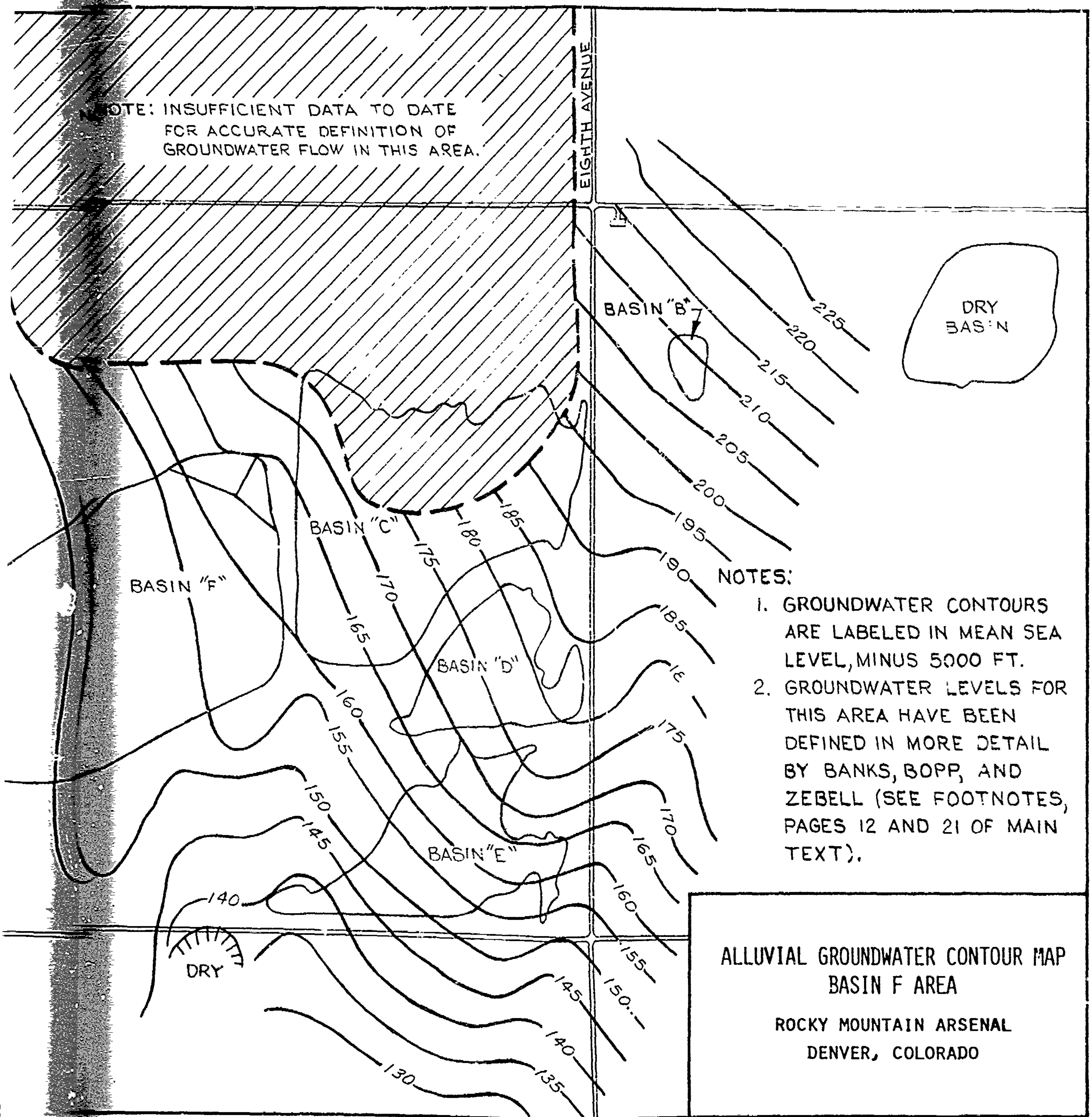


BOG
NINTH AVENUE
"D" STREET
INTERIM CONTAINMENT SYSTEM
150
145
140
135
130
DRY
N
150
"C" STREET
SCALE IN FEET
800 0 800 1600 2400

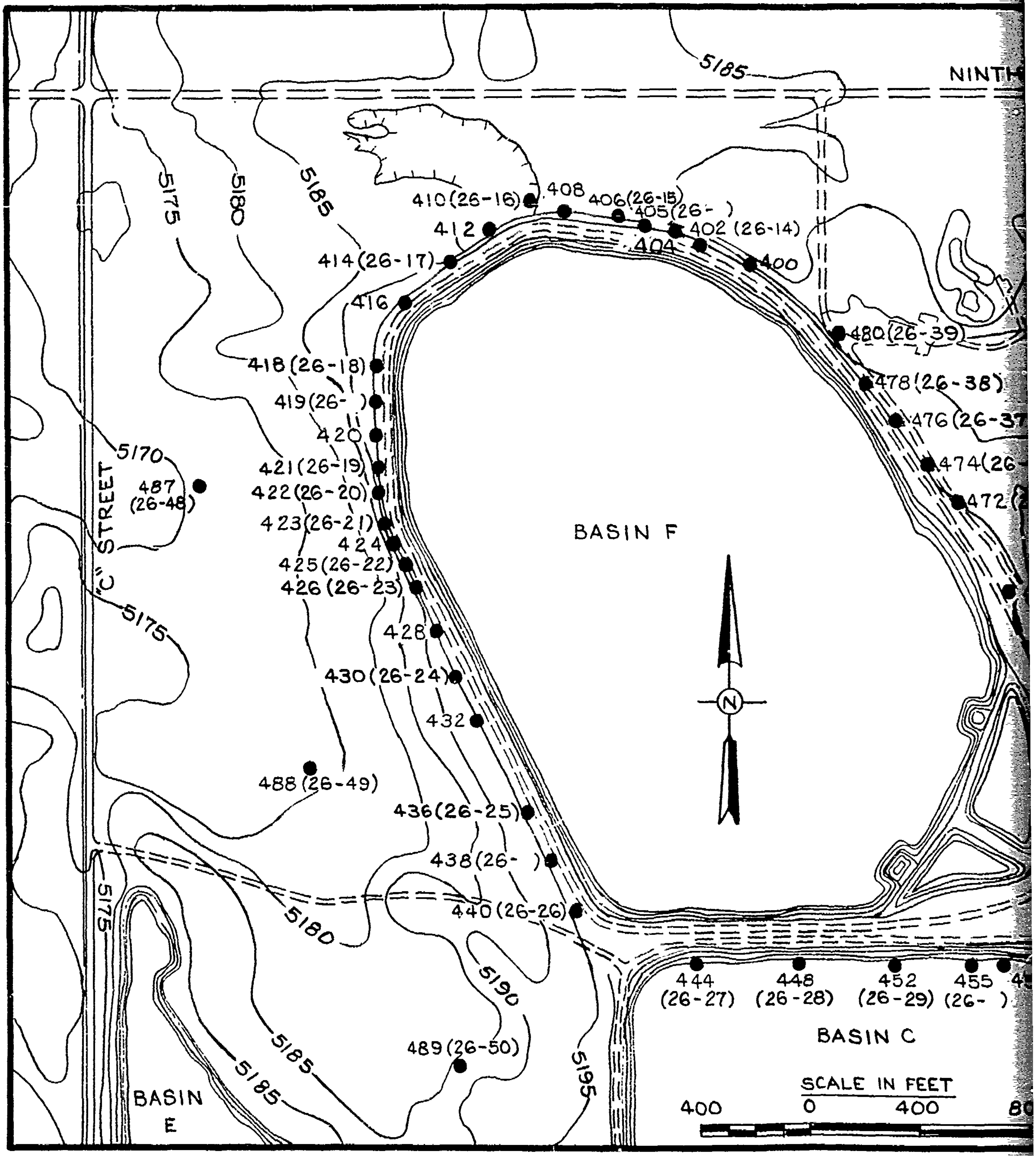


ALLUVIAL GROUNDWATER CONTOUR MAP
BASIN F AREA

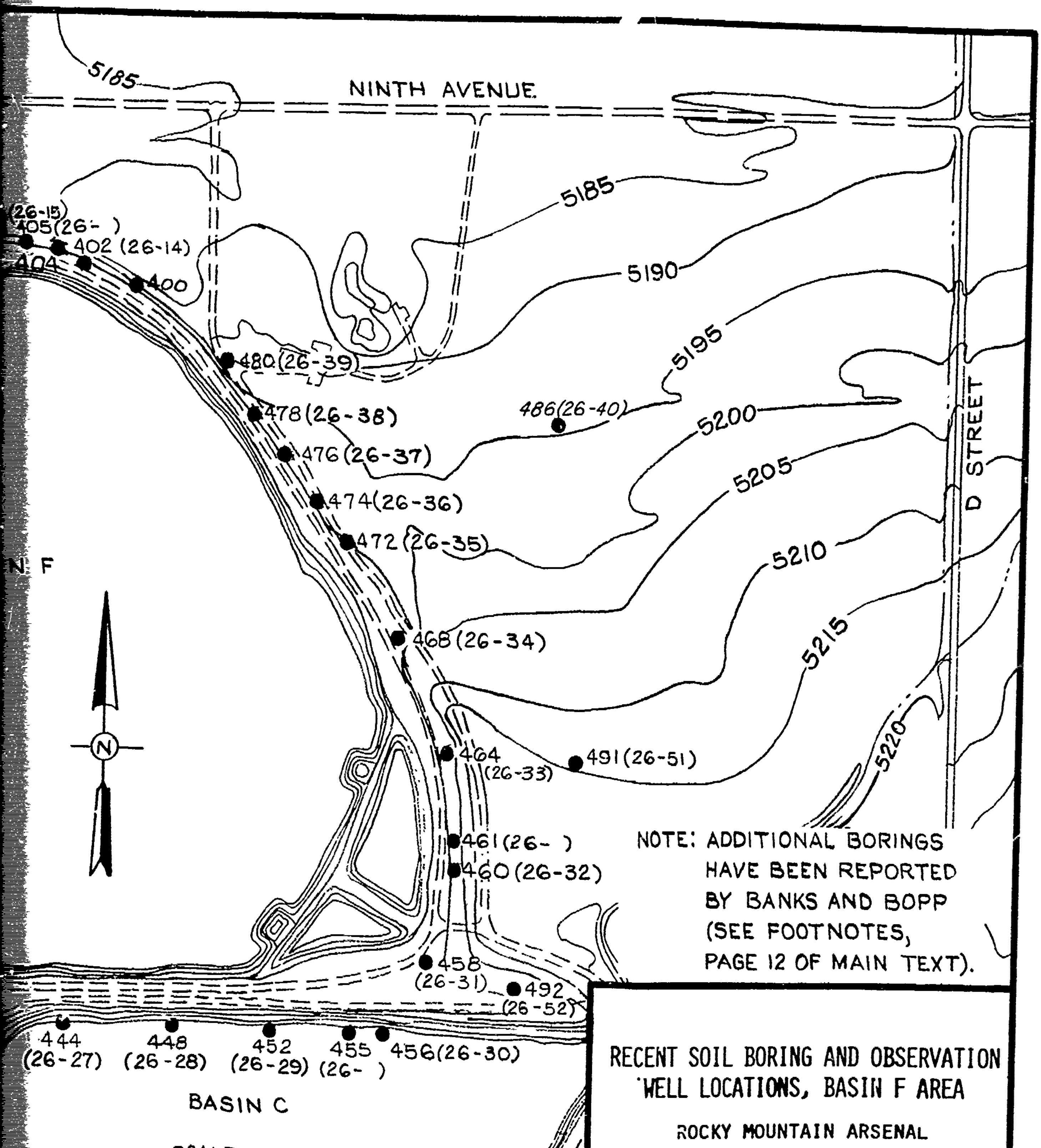
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PLATE I

2



NINTH
5185
5175
5180
5185
410(26-16)
408
406(26-15)
405(26-)
402 (26-14)
404
400
412
414(26-17)
416
480(26-39)
418(26-18)
478(26-38)
419(26-)
476(26-37
420
474(26-
5170
421(26-19)
487
(26-48)
422(26-20)
472(
"C" STREET
423(26-21)
BASIN F
424
425(26-22)
426 (26-23)
5175
428
430(26-24)
432
488(26-49)
436(26-25)
438(26-)
440(26-26)
5175
5180
444
(26-27)
448
(26-28)
452
(26-29)
455
(26-)
5190
BASIN C
5185
5185
489(26-50)
5195
SCALE IN FEET
400 0 400 80
BASIN
E



RECENT SOIL BORING AND OBSERVATION WELL LOCATIONS, BASIN F AREA

ROCKY MOUNTAIN ARSENAL

DENVER, COLORADO

PLATE 2

2

UNIFIED SOIL CLASSIFICATION

MAJOR DIVISION		TYPE	LETTER SYMBOL	SYMBOL	TYPICAL NAMES
COARSE - GRAINED SOILS More than half of material is larger than No 200 sieve size	GRAVELS More than half of coarse fraction is larger than No 4 sieve size	CLEAN GRAVEL (Little or No Fines)	GW		GRAVEL, Well Graded, gravel-sand mixtures, little or no fines
			GP		GRAVEL, Poorly Graded, gravel-sand mixtures, little or no fines
		GRAVEL WITH FINES (Appreciable Amount of Fines)	GM		SILTY GRAVEL, gravel-sand-silt mixtures
			GC		CLAYEY GRAVEL, gravel-sand-clay mixtures
	SANDS More than half of coarse fraction is smaller than No 4 sieve size	CLEAN SAND (Little or No Fines)	SW		SAND, Well-Graded, gravelly sands
			SP		SAND, Poorly-Graded, gravelly sands
		SANDS WITH FINES (Appreciable Amount of Fines)	SM		SILTY SAND, sand-silt mixtures
			SC		CLAYEY SAND, sand-clay mixtures
FINE - GRAINED SOILS More than half the material is smaller than No 200 sieve size		SILTS AND CLAYS (Liquid Limit < 50)	ML		SILT & very fine sand, silty or clayey fine sand or clayey silt with slight plasticity
			CL		LEAN CLAY; Sandy Clay, Silty Clay; of low to medium plasticity
			OL		ORGANIC SILTS and organic silty clays of low plasticity
		SILTS AND CLAYS (Liquid Limit > 50)	MH		SILT, fine sandy or silty soil with high plasticity
			CH		FAT CLAY, inorganic clay of high plasticity
			OH		ORGANIC CLAYS of medium to high plasticity, organic silts
HIGHLY ORGANIC SOILS			Pt		PEAT, and other highly organic soil
WOOD			Wd		WOOD
SHELLS			Sl		SHELLS
NO SAMPLE					
			Sh		SHALE

NOTE: Soils possessing characteristics of two groups are designated by combinations of group symbols

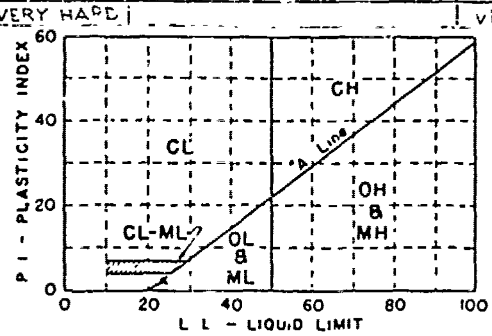
DESCRIPTIVE SYMBOLS

COLOR

COLOR	SYMBOL
TAN	T
YELLOW	Y
RED	R
BLACK	BK
GRAY	Gr
LIGHT GRAY	lGr
DARK GRAY	dGr
BROWN	Br
LIGHT BROWN	lBr
DARK BROWN	dBr
BROWNISH-GRAY	br Gr
GRAYISH-BROWN	gyBr
GREENISH-GRAY	gnGr
GRAYISH-GREEN	gyGn
GREEN	Gn
BLUE	Bl
BLUE-GREEN	BlGn
WHITE	Wh
MOTTLED	Mot

CONSISTENCY FOR COHESIVE SOILS

CONSISTENCY		SYMBOL
VERY SOFT		vSo
SOFT		So
MEDIUM		M
STIFF		St
VERY STIFF		vSt
HARD		H
VERY HARD		vH



PLASTICITY CHART

For classification of fine-grained soils

MODIFICATIONS

MODIFICATION	SYMBOL
Traces	Tr-
Fine	F
Medium	M
Coarse	C
Concretions	cc
Rootlets	rt
Lignite fragments	lg
Shale fragments	sh
Sandstone fragments	sds
Shell fragments	slf
Organic matter	O
Clay strata or lenses	CS
Silt strata or lenses	SIS
Sand strata or lenses	SS
Sandy	S
Gravelly	G
Boulders	B
Slickensides	SL
Wood	Wd
Oxidized	Ox
Crumbly	Cr
Loose	Lo
Vegetation	Veg

ATION

NAMES
little or no fines
little or no fines
nd or clayey silt with slight plasticity
to medium plasticity
low plasticity
sticity
ty
city, organic silts

inations of group symbols

MODIFICATIONS	
MODIFICATION	SYMBOL
Traces	Tr-
Fine	F
Medium	M
Coarse	C
Concretions	cc
Rootlets	rt
Lignite fragments	lg
Shale fragments	sh
Sandstone fragments	sds
Shell fragments	slf
Organic matter	O
Clay strata or lenses	CS
Silt strata or lenses	SIS
Sand strata or lenses	SS
Sandy	S
Gravelly	G
Boulders	B
Slickensides	SL
Wood	wd
Oxidized	Ox
Crumbly	Cr
Loose	Lo
Vegetation	Veg

NOTES:
FIGURES TO LEFT OF BORING UNDER COLUMN "W OR D_{10}"
Are natural water contents in percent dry weight
When underlined denotes D_{10} size in mm *
FIGURES TO LEFT OF BORING UNDER COLUMNS "LL" AND "PL"
Are liquid and plastic limits, respectively
SYMBOLS TO LEFT OF BORING
∇ Ground-water surface and date observed
(C) Denotes location of consolidation test **
(S) Denotes location of consolidated-drained direct shear test **
(R) Denotes location of consolidated-undrained triaxial compression test **
(Q) Denotes location of unconsolidated-undrained triaxial compression test **
(T) Denotes location of sample subjected to consolidation test and each of the above three types of shear tests **
FW Denotes free water
FIGURES TO RIGHT OF BORING
Are values of cohesion in lbs/sq ft from unconfined compression tests
In parenthesis are driving resistances in blows per foot determined with a standard split spoon sampler ($1\frac{3}{8}$" ID, 2" OD) and a 140 lb driving hammer with a 30" drop
Where underlined with a solid line denotes laboratory permeability in centimeters per second of undisturbed sample
Where underlined with a dashed line denotes laboratory permeability in centimeters per second of sample remoulded to the estimated natural void ratio

* The D_{10} size of a soil is the grain diameter in millimeters of which 10% of the soil is finer, and 90% coarser than size D_{10}

**Results of these tests are available for inspection in the U S Army Engineer District Office, if these symbols appear beside the boring logs on the drawings

GENERAL NOTES:

While the borings are representative of subsurface conditions at their respective locations and for their respective vertical reaches, local variations characteristic of the subsurface materials of the region are anticipated and, if encountered, such variations will not be considered as differing materially within the purview of clause 4 of the contract

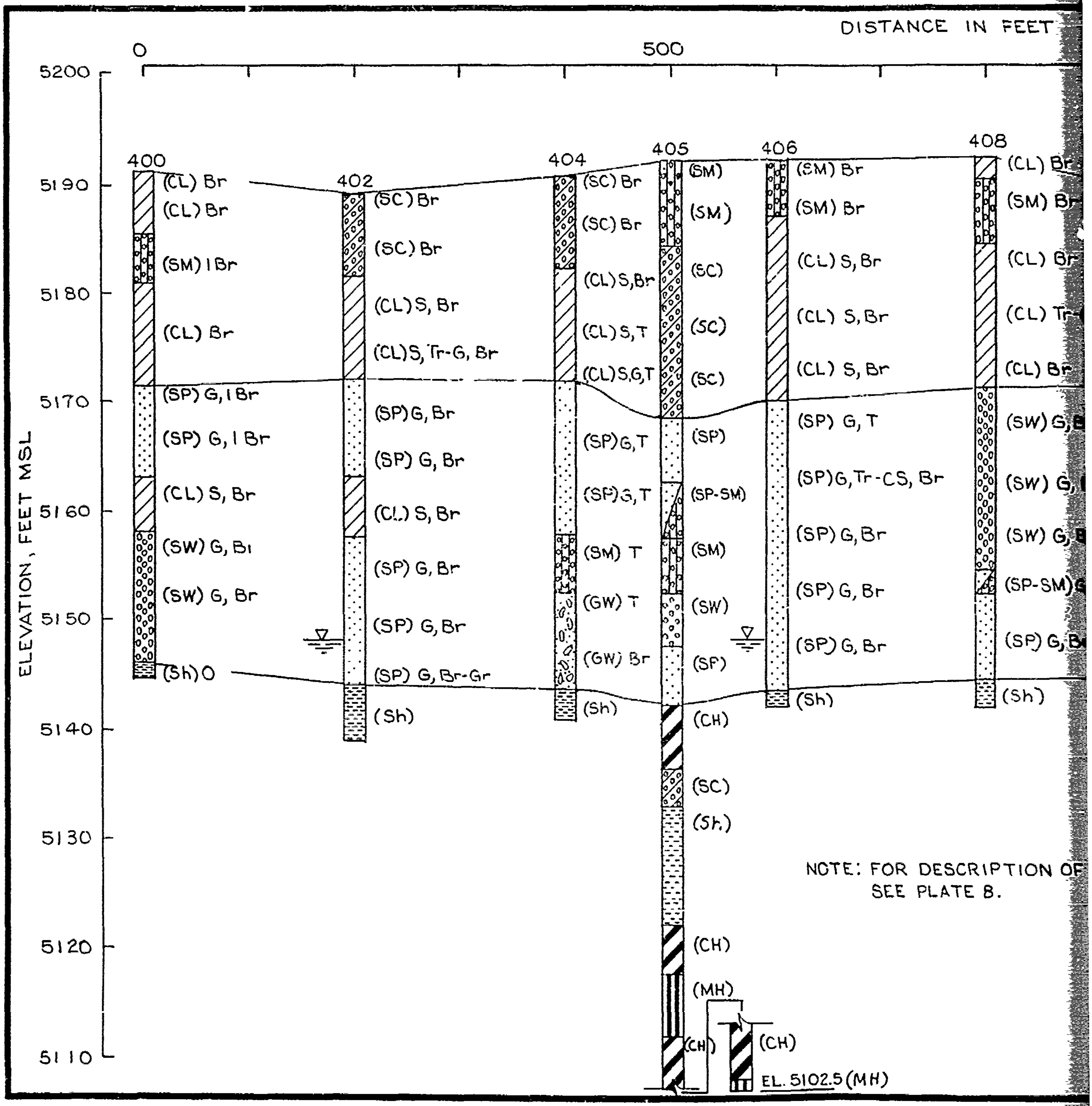
Ground-water elevations shown on the boring logs represent ground-water surfaces encountered on the dates shown. Absence of water surface data on certain borings implies that no ground-water data is available, but does not necessarily mean that ground water will not be encountered at the locations or within the vertical reaches of these borings

Consistency of cohesive soils shown on the boring logs is based on driller's log and visual examination and is approximate, except within those vertical reaches of the borings where shear strengths from unconfined compression tests are shown

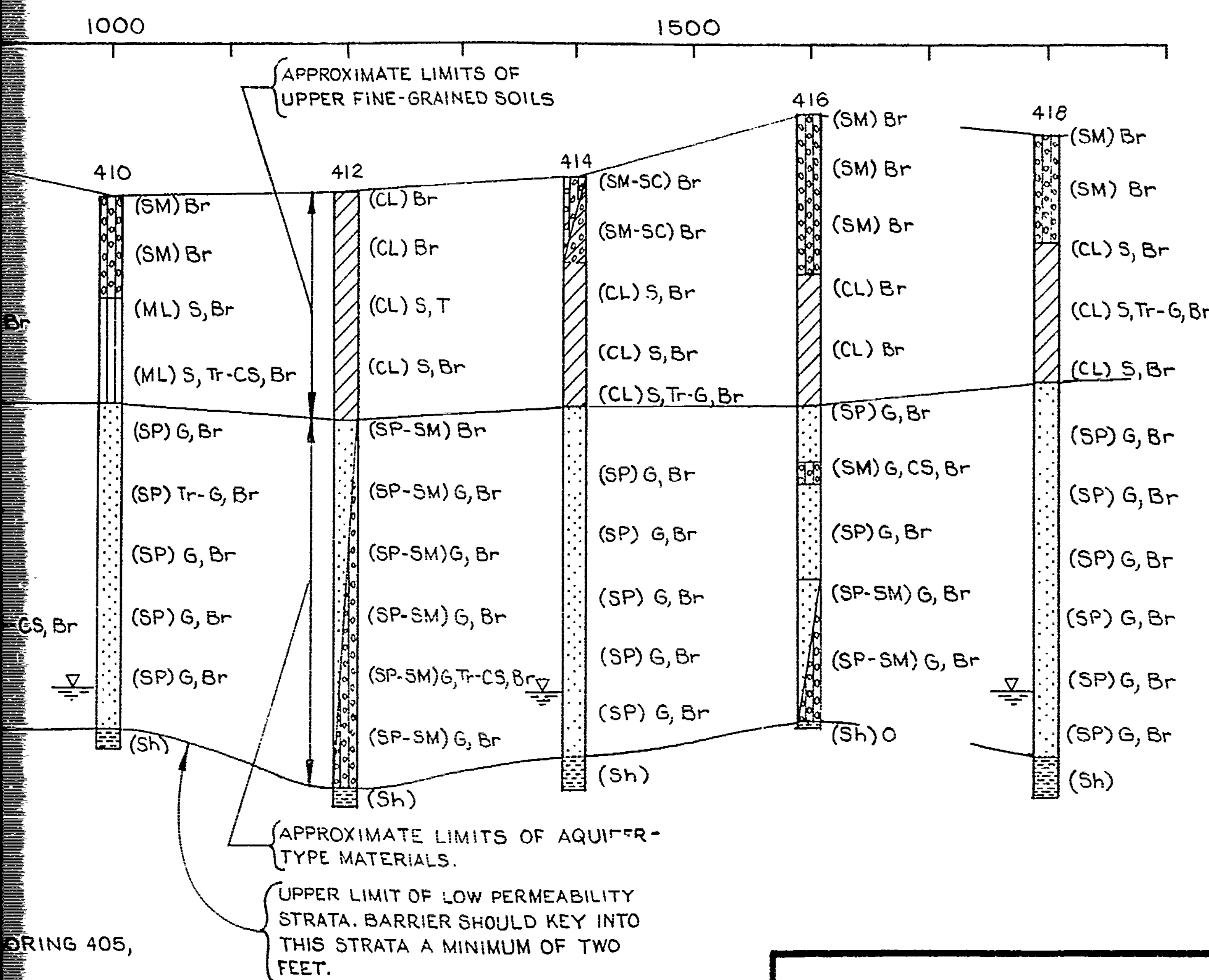
SOILS BORING LEGEND
BASIN F

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PLATE 3



DISTANCE IN FEET
0
500
5200
5190
5180
5170
5160
5150
5140
5130
5120
5110
ELEVATION, FEET MSL
400
(CL) Br
(CL) Br
(SM) I Br
(CL) Br
(SP) G, I Br
(SP) G, I Br
(CL) S, Br
(SW) G, Br
(SW) G, Br
(Sh) O
402
(SC) Br
(SC) Br
(CL) S, Br
(CL) S, Tr-G, Br
(SP) G, Br
(SP) G, Br
(CL) S, Br
(SP) G, Br
(SP) G, Br
(SP) G, Br-Gr
(Sh)
404
(SC) Br
(SC) Br
(CL) S, Br
(CL) S, T
(CL) S, G, T
(SP) G, T
(SP) G, T
(SM) T
(GW) T
(GW) Br
(Sh)
405
(SM)
(SM)
(SC)
(SC)
(SC)
(SP)
(SP-SM)
(SM)
(SW)
(SP)
(CH)
(SC)
(Sh)
(CH)
(MH)
(CH)
(CH)
EL. 5102.5 (MH)
406
(SM) Br
(SM) Br
(CL) S, Br
(CL) S, Br
(CL) S, Br
(SP) G, T
(SP) G, Tr-CS, Br
(SP) G, Br
(SP) G, Br
(SP) G, Br
(Sh)
408
(CL) Br
(SM) Br
(CL) Br
(CL) Tr-
(CL) Br
(SW) G,
(SW) G,
(SW) G,
(SP-SM)
(SP) G,
(Sh)
NOTE: FOR DESCRIPTION OF
SEE PLATE 8.

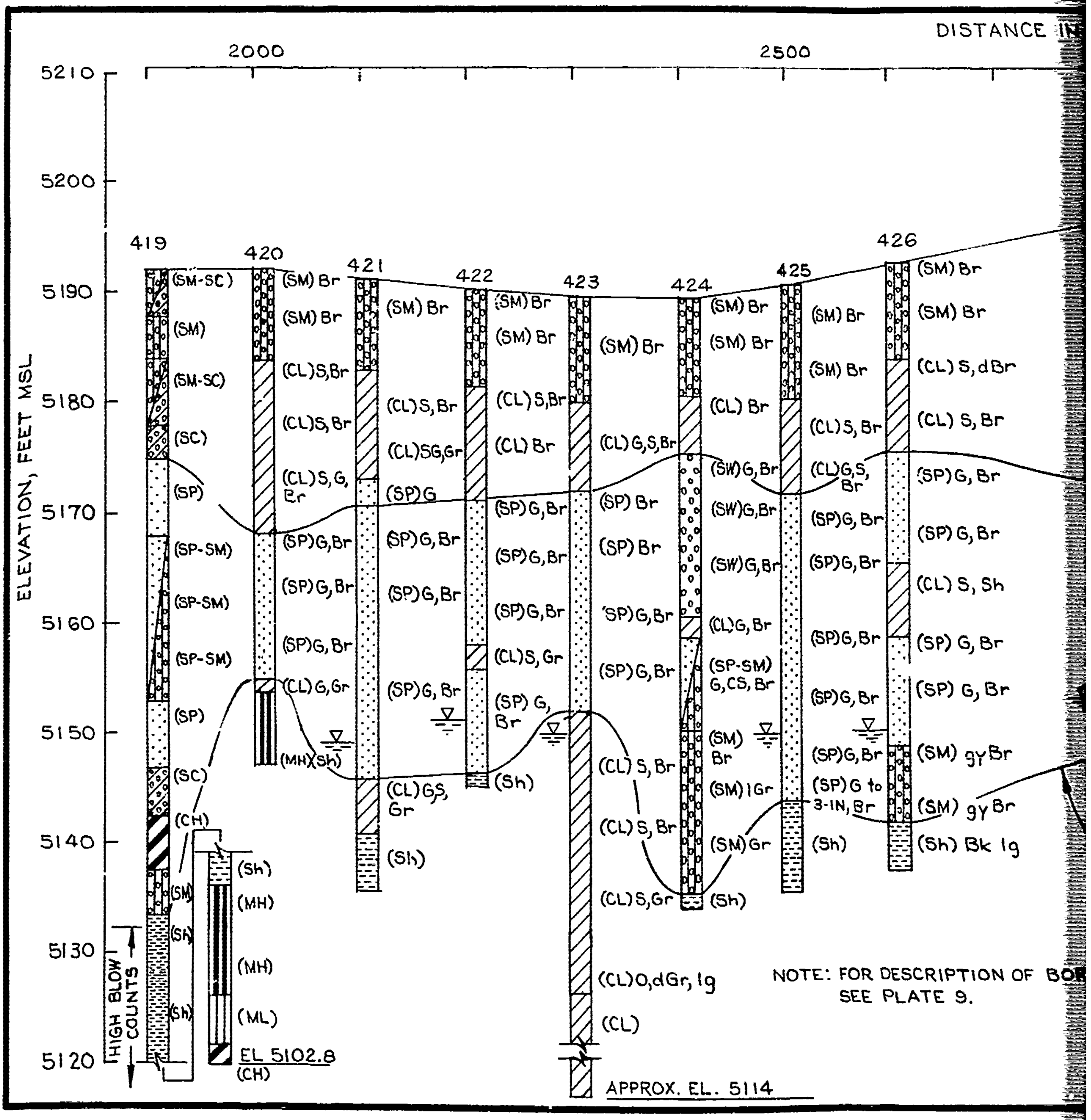


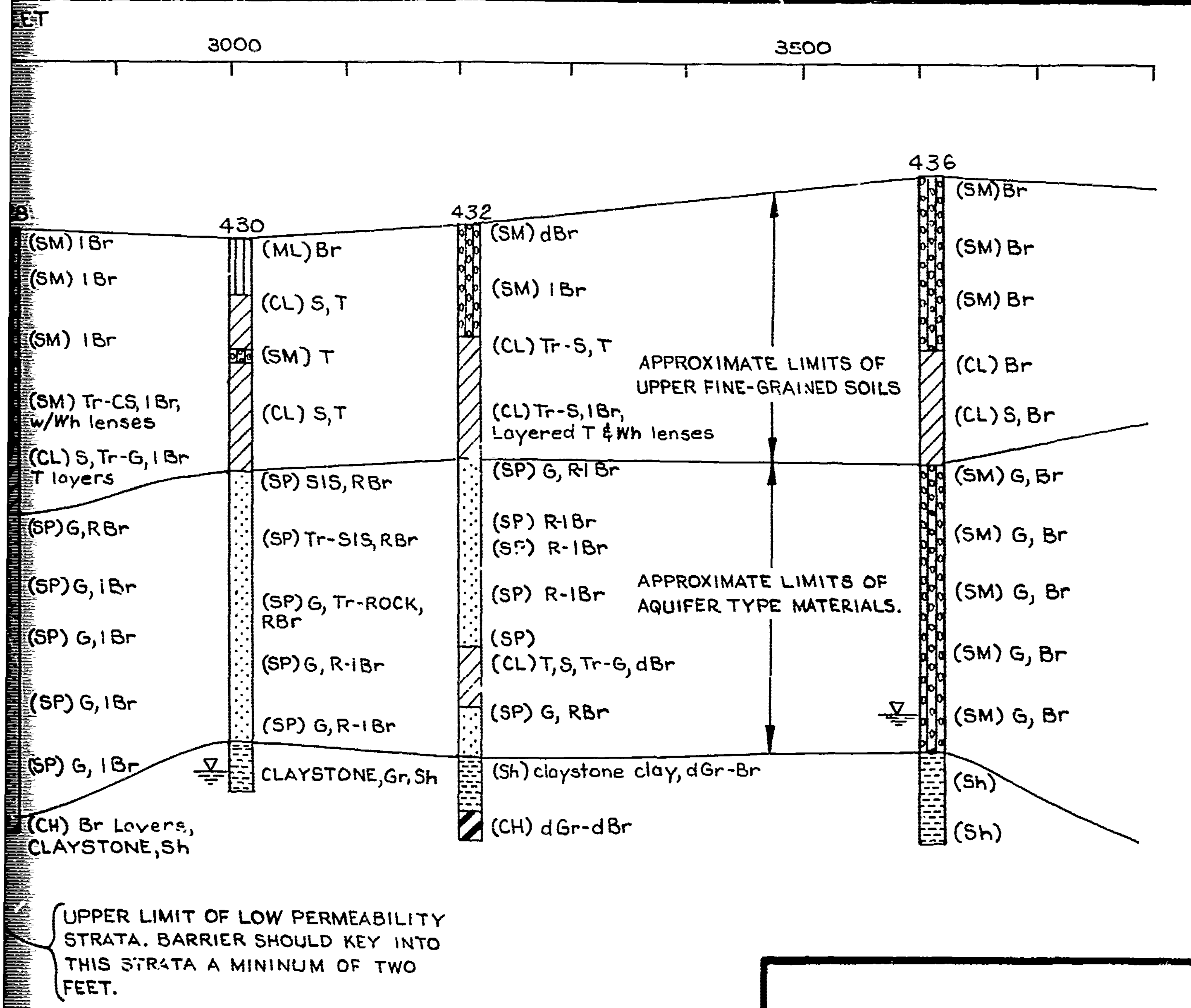
BORING PROFILE
NORTHERN CURVE OF BASIN F

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PLATE 4

2


DISTANCE IN
2000
2500
ELEVATION, FEET MSL
5210
5200
5190
5180
5170
5160
5150
5140
5130
5120
419
420
421
422
423
424
425
426
(SM-SC)
(SM)
(SM-SC)
(SC)
(SP)
(SP-SM)
(SP-SM)
(SP-SM)
(SP)
(SC)
(CH)
(SM)
(Sh)
(Sh)
HIGH BLOW COUNTS
(SM) Br
(SM) Br
(CL) S, Br
(CL) S, Br
(CL) S, G, Br
(SP) G, Br
(SP) G, Br
(SP) G, Br
(CL) G, Gr
(MH)(Sh)
(Sh)
(MH)
(MH)
(ML)
EL 5102.8
(CH)
(SM) Br
(CL) S, Br
(CL) SG, Gr
(SP) G
(SP) G, Br
(SP) G, Br
(SP) G, Br
(CL) G, S, Gr
(Sh)
(SM) Br
(SM) Br
(CL) S, Br
(CL) Br
(SP) G, Br
(SP) G, Br
(SP) G, Br
(CL) S, Gr
(SP) G, Br
(Sh)
(SM) Br
(CL) G, S, Br
(SP) Br
(SP) Br
(SP) G, Br
(SP) G, Br
(CL) S, Br
(CL) S, Br
(CL) S, Gr
(CL) O, dGr, lg
(CL)
APPROX. EL. 5114
(SM) Br
(SM) Br
(CL) Br
(SW) G, Br
(SW) G, Br
(SW) G, Br
(CL) G, Br
(SP-SM) G, CS, Br
(SM) Br
(SM) lGr
(SM) Gr
(Sh)
(SM) Br
(SM) Br
(CL) S, Br
(CL) G, S, Br
(SP) G, Br
(SP) G, Br
(SP) G, Br
(SP) G, Br
(SP) G, Br
(SP) G to 3-IN, Br
(Sh)
(SM) Br
(SM) Br
(CL) S, dBr
(CL) S, Br
(SP) G, Br
(SP) G, Br
(CL) S, Sh
(SP) G, Br
(SP) G, Br
(SM) gy Br
(SM) gy Br
(Sh) Bk lg
NOTE: FOR DESCRIPTION OF BOR
SEE PLATE 9.

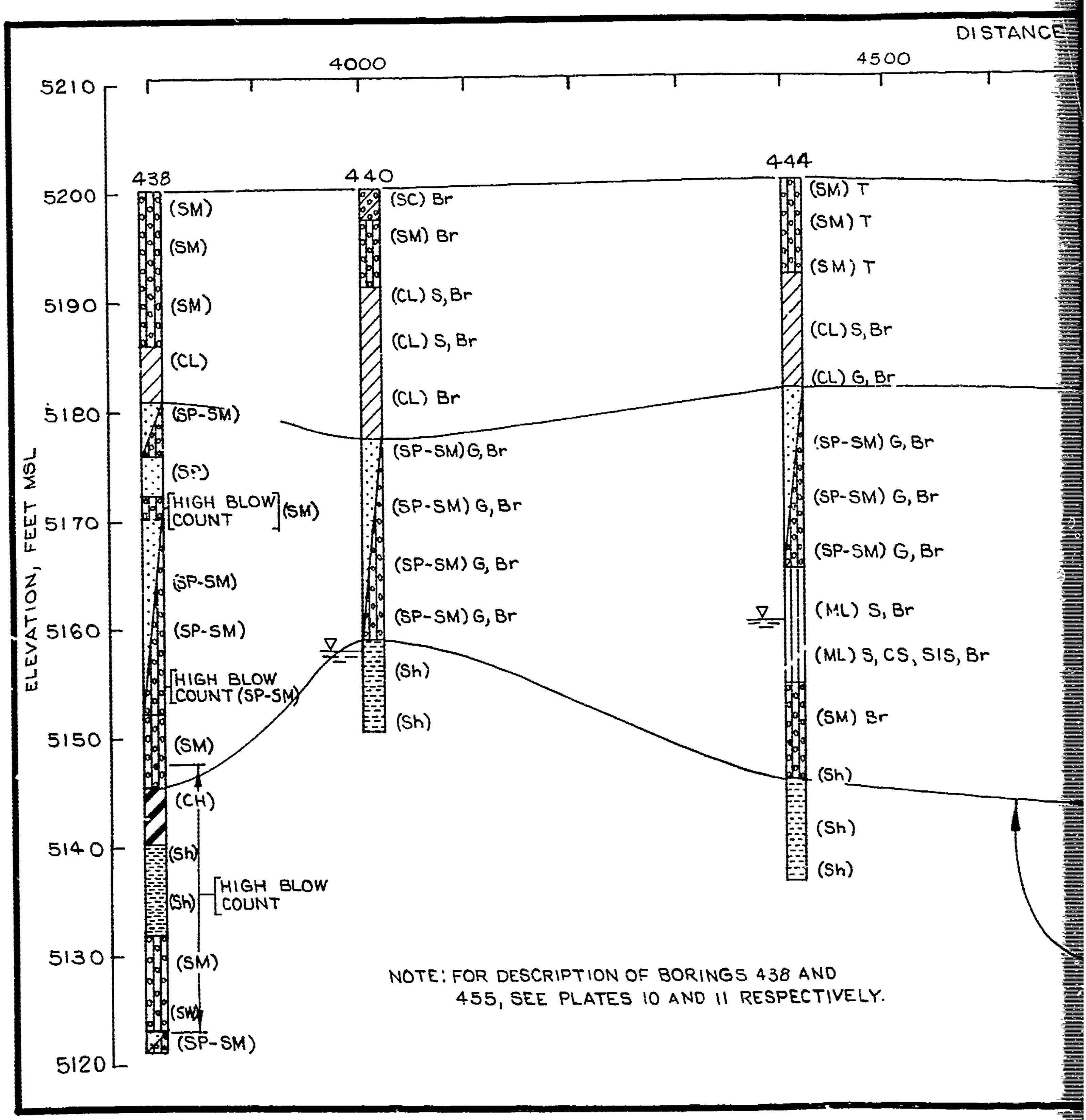


BORING PROFILE
WESTERN BOUNDARY OF BASIN F

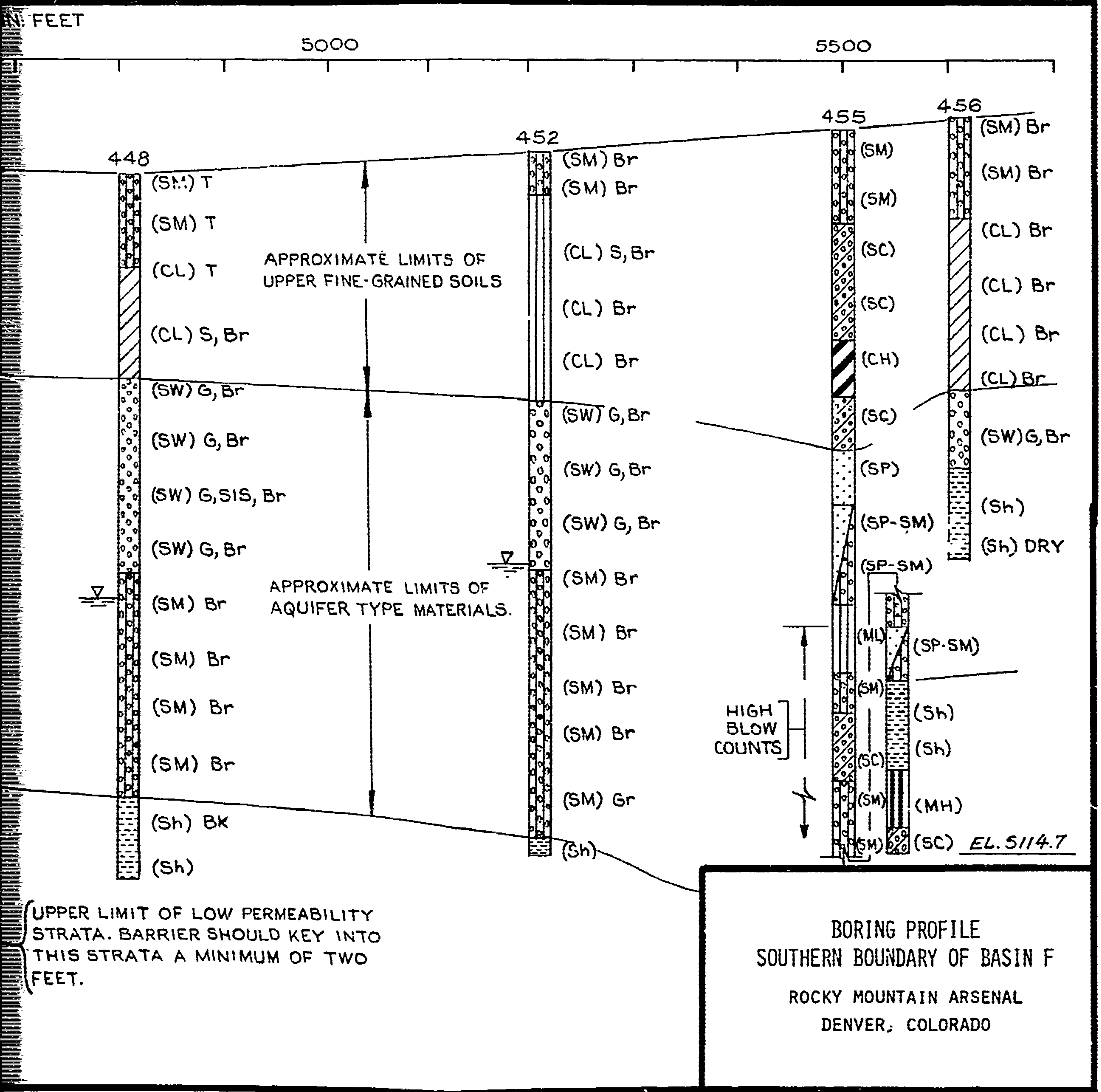
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PLATE 5

2



DISTANCE
4000
4500
5210
5200
5190
5180
5170
5160
5150
5140
5130
5120
ELEVATION, FEET MSL
438
440
444
(SM)
(SM)
(SM)
(CL)
(SP-SM)
(SP)
HIGH BLOW COUNT (SM)
(SP-SM)
(SP-SM)
HIGH BLOW COUNT (SP-SM)
(SM)
(CH)
(Sh)
(Sh)
HIGH BLOW COUNT
(SM)
(SW)
(SP-SM)
(SC) Br
(SM) Br
(CL) S, Br
(CL) S, Br
(CL) Br
(SP-SM) G, Br
(SP-SM) G, Br
(SP-SM) G, Br
(SP-SM) G, Br
(Sh)
(Sh)
(SM) T
(SM) T
(SM) T
(CL) S, Br
(CL) G, Br
(SP-SM) G, Br
(SP-SM) G, Br
(SP-SM) G, Br
(ML) S, Br
(ML) S, CS, SIS, Br
(SM) Br
(Sh)
(Sh)
(Sh)
NOTE: FOR DESCRIPTION OF BORINGS 438 AND 455, SEE PLATES 10 AND 11 RESPECTIVELY.

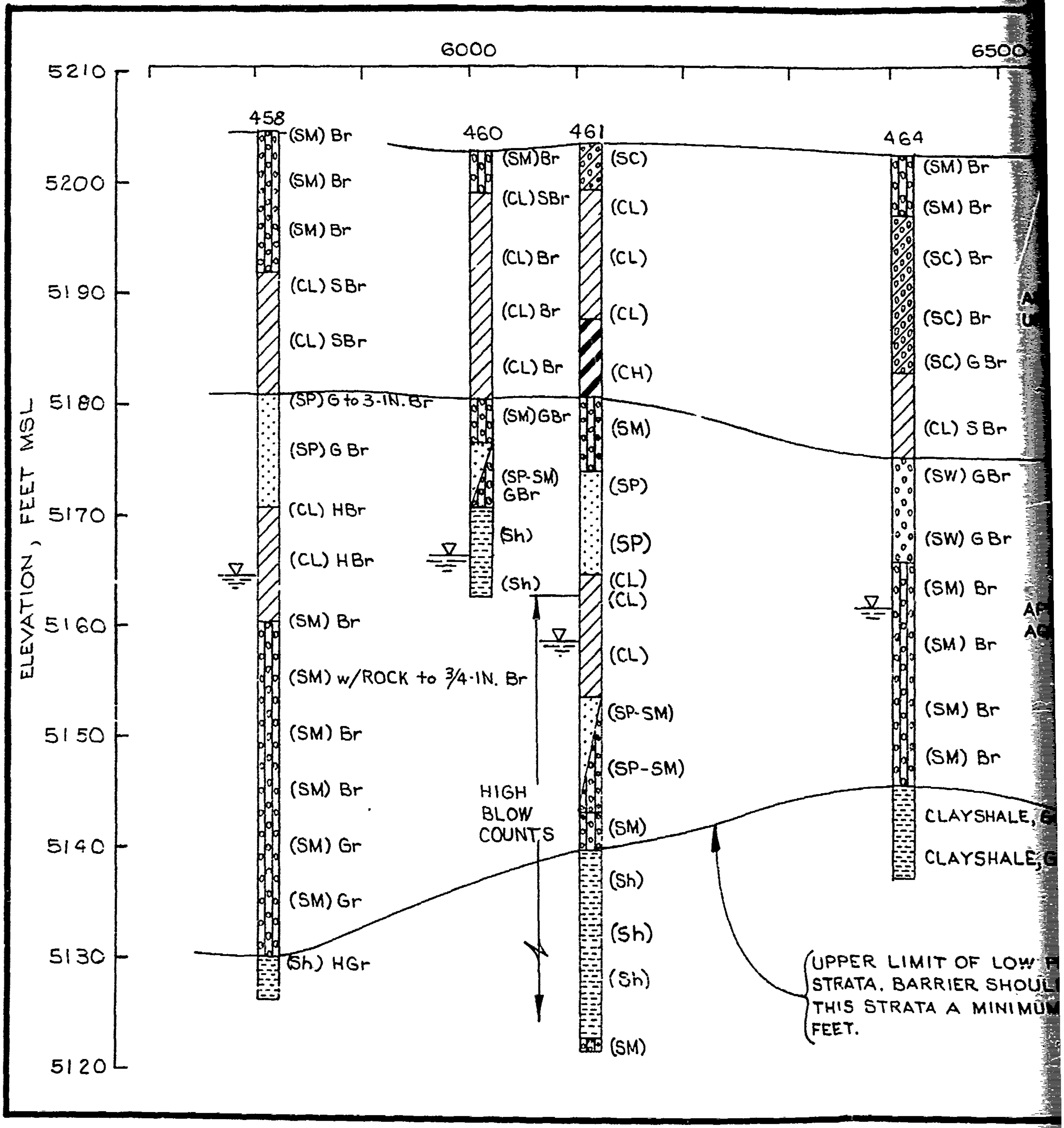


BORING PROFILE
SOUTHERN BOUNDARY OF BASIN F

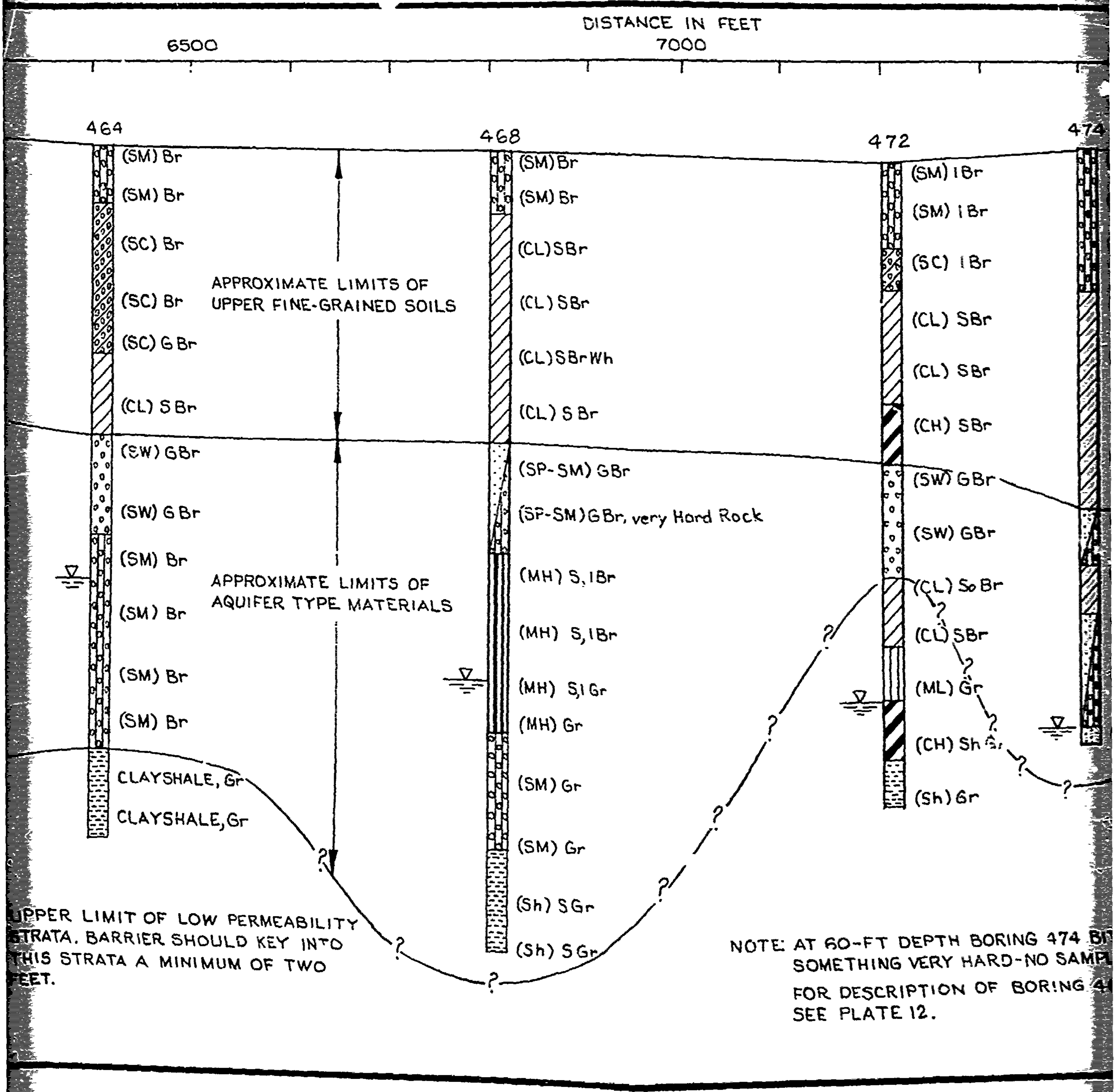
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

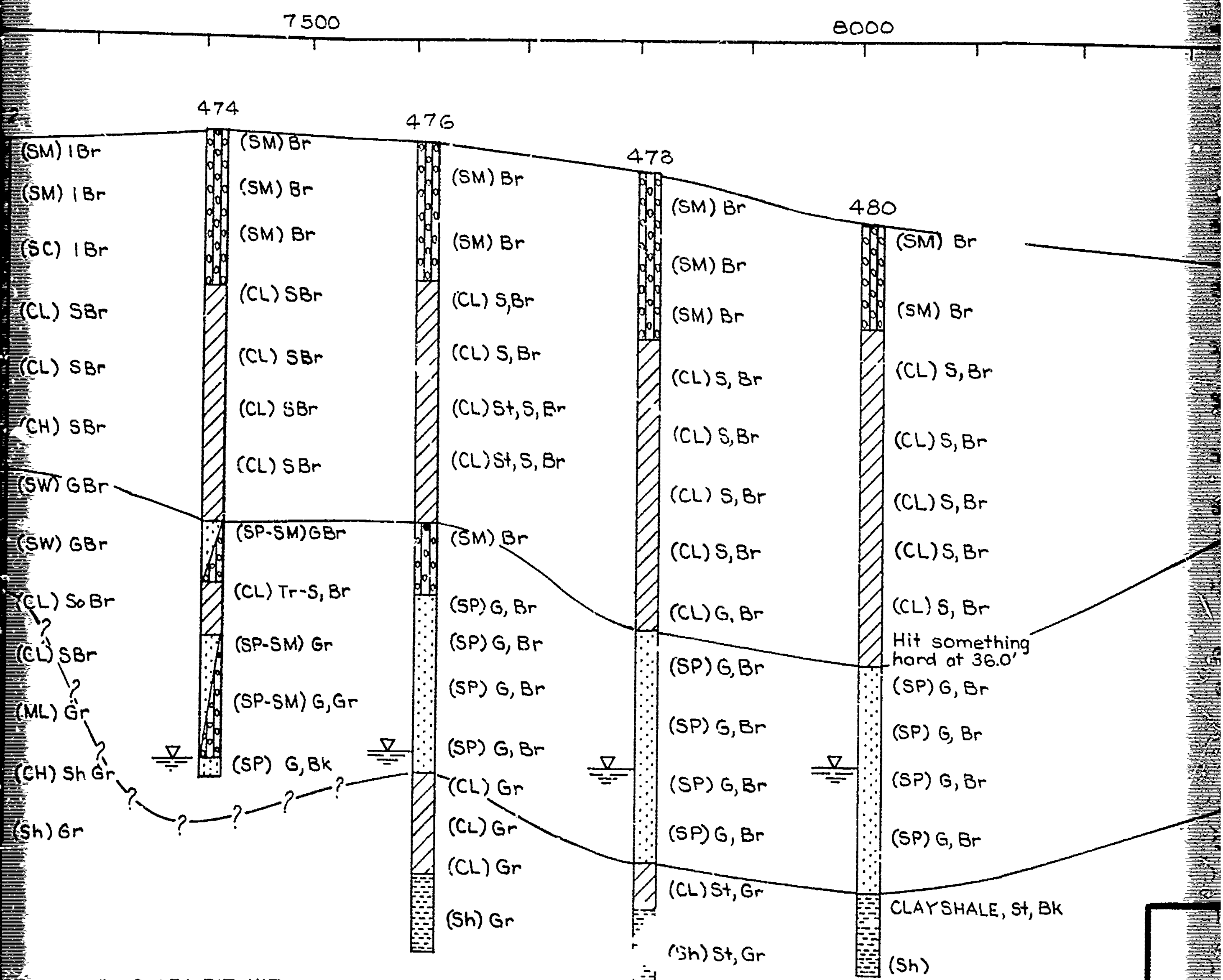
PLATE 6

2

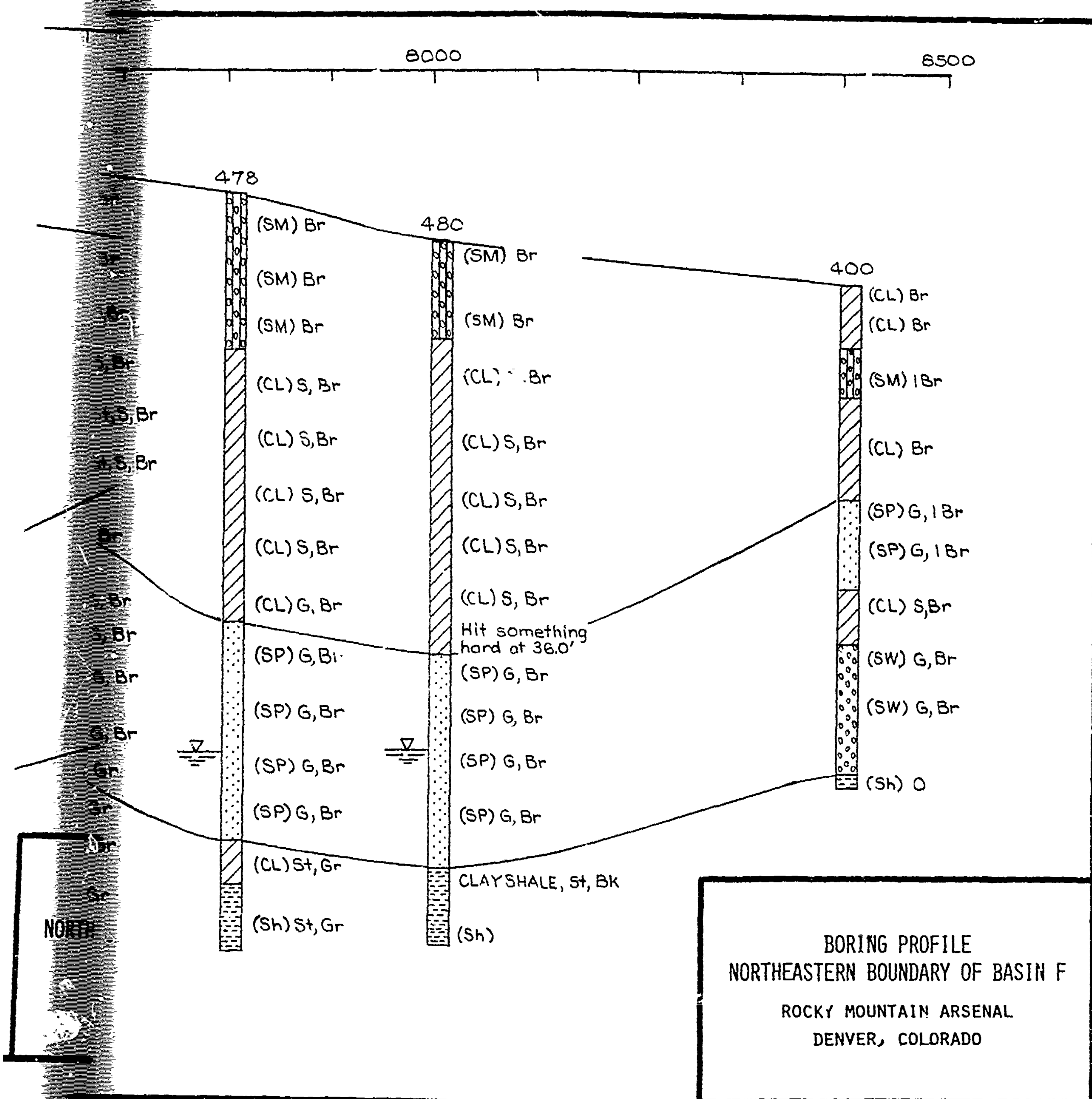


6000
6500
5210
5200
5190
5180
5170
5160
5150
5140
5130
5120
ELEVATION, FEET MSL
458
460
461
464
(SM) Br
(SM) Br
(SM) Br
(CL) SBr
(CL) SBr
(SP) G to 3-IN. Br
(SP) G Br
(CL) HBr
(CL) HBr
(SM) Br
(SM) w/ROCK to 3/4-IN. Br
(SM) Br
(SM) Br
(SM) Gr
(SM) Gr
(Sh) HGr
(SM)Br
(CL)SBr
(CL) Br
(CL) Br
(CL) Br
(SM)GBr
(SP-SM) GBr
(Sh)
(Sh)
(SC)
(CL)
(CL)
(CL)
(CH)
(SM)
(SP)
(SP)
(CL)
(CL)
(CL)
(SP-SM)
(SP-SM)
(SM)
(Sh)
(Sh)
(Sh)
(SM)
(SM) Br
(SM) Br
(SC) Br
(SC) Br
(SC) G Br
(CL) S Br
(SW) GBr
(SW) G Br
(SM) Br
(SM) Br
(SM) Br
(SM) Br
CLAYSHALE,
CLAYSHALE,
HIGH BLOW COUNTS
UPPER LIMIT OF LOW
STRATA. BARRIER SHOUL
THIS STRATA A MINIMUM
FEET.


DISTANCE IN FEET
6500
7000
464
468
472
474
(SM) Br
(SM) Br
(SC) Br
(SC) Br
(SC) G Br
(CL) S Br
(SW) GBr
(SW) G Br
(SM) Br
(SM) Br
(SM) Br
(SM) Br
CLAYSHALE, Gr
CLAYSHALE, Gr
APPROXIMATE LIMITS OF
UPPER FINE-GRAINED SOILS
APPROXIMATE LIMITS OF
AQUIFER TYPE MATERIALS
(SM) Br
(SM) Br
(CL) SBr
(CL) SBr
(CL) SBrWh
(CL) S Br
(SP-SM) GBr
(SP-SM) GBr, very Hard Rock
(MH) S, l Br
(MH) S, l Br
(MH) S, l Gr
(MH) Gr
(SM) Gr
(SM) Gr
(Sh) S Gr
(Sh) S Gr
(SM) l Br
(SM) l Br
(SC) l Br
(CL) SBr
(CL) SBr
(CH) SBr
(SW) GBr
(SW) GBr
(CL) So Br
(CL) SBr
(ML) Gr
(CH) Sh Gr
(Sh) Gr
UPPER LIMIT OF LOW PERMEABILITY STRATA. BARRIER SHOULD KEY INTO THIS STRATA A MINIMUM OF TWO FEET.
NOTE: AT 60-FT DEPTH BORING 474 BI[T]
SOMETHING VERY HARD-NO SAMP[LE]
FOR DESCRIPTION OF BORING 4[...]
SEE PLATE 12.



EPTH BORING 474 BIT HIT
ERY HARD-NO SAMPLE.
TION OF BORING 461,
12.

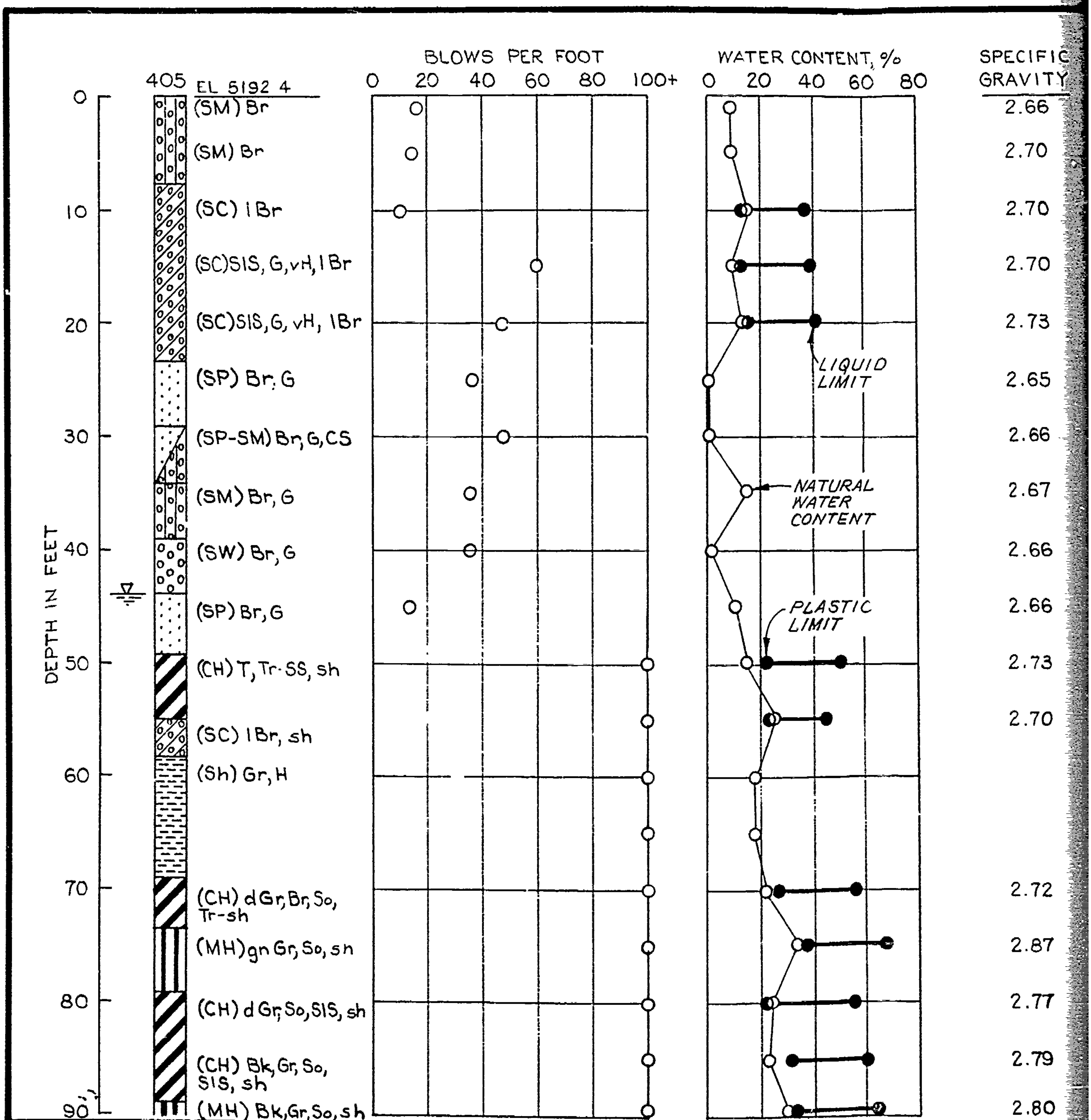


BORING PROFILE
NORTHEASTERN BOUNDARY OF BASIN F

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PLATE 7

4



BLOWS PER FOOT
0 20 40 60 80 100+
WATER CONTENT, %
0 20 40 60 80
SPECIFIC GRAVITY
405 EL 5192 4
DEPTH IN FEET
0 10 20 30 40 50 60 70 80 90
(SM) Br
(SM) Br
(SC) l Br
(SC) SlS, G, vH, l Br
(SC) SlS, G, vH, l Br
(SP) Br, G
(SP-SM) Br, G, CS
(SM) Br, G
(SW) Br, G
(SP) Br, G
(CH) T, Tr-SS, sh
(SC) l Br, sh
(Sh) Gr, H
(CH) dGr, Br, So, Tr-sh
(MH) gn Gr, So, sh
(CH) d Gr, So, SlS, sh
(CH) Bk, Gr, So, SlS, sh
(MH) Bk, Gr, So, sh
LIQUID LIMIT
NATURAL WATER CONTENT
PLASTIC LIMIT
2.66
2.70
2.70
2.70
2.73
2.65
2.66
2.67
2.66
2.66
2.73
2.70
2.72
2.87
2.77
2.79
2.80

80

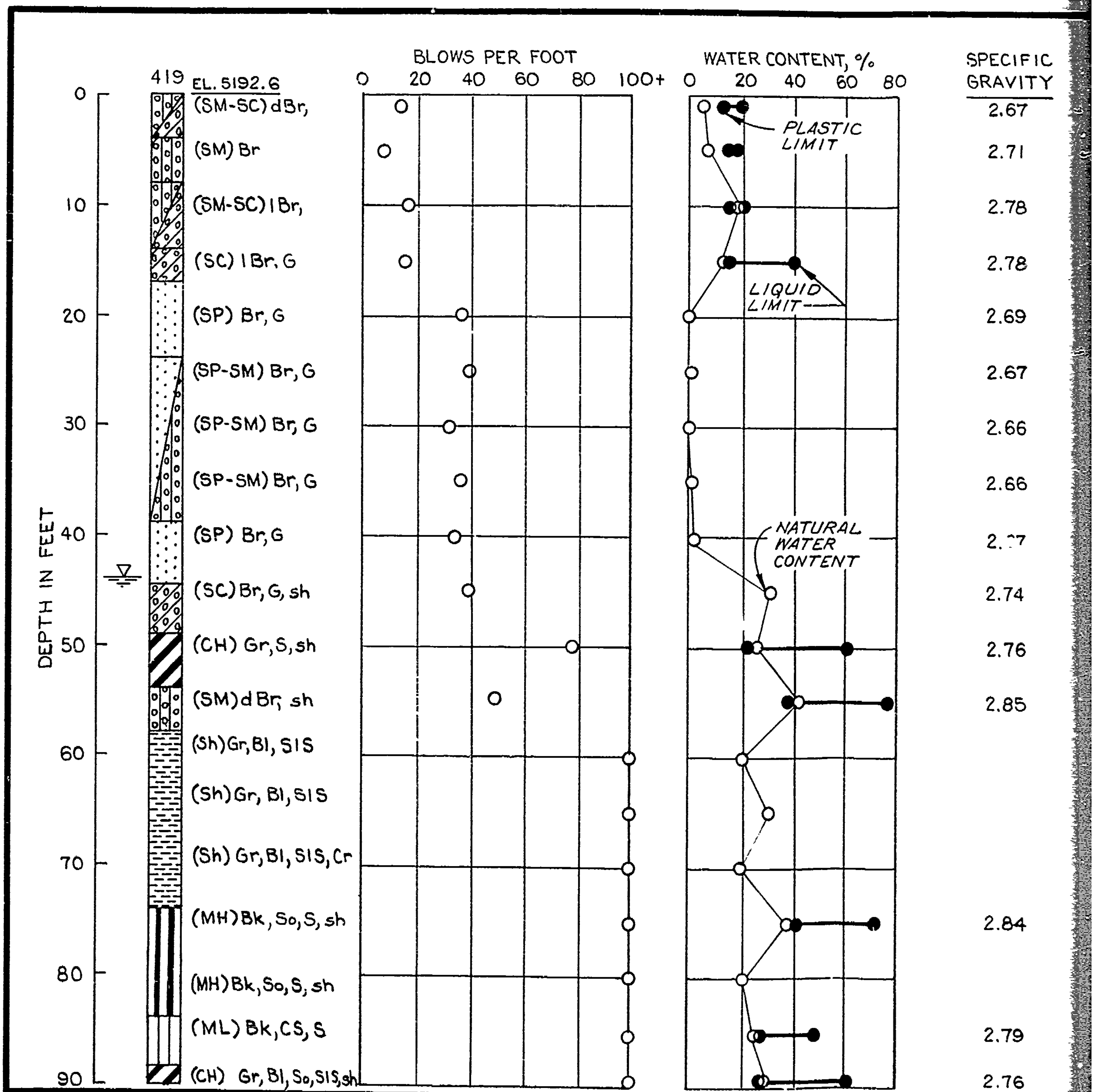
SPECIFIC GRAVITY	ESTIMATED VALUES γ_W, PCF	Ø, DEG	C, PSF	POROSITY
2.66				
2.70				
2.70	132	32	900	
2.70				
2.73				
2.65				
2.66				
2.67	132	37	950	
2.66				
2.66				22.3
2.73				28.5
2.70				40.0
2.72	115	15	840	37.1
2.87				49.2
2.77				39.0
2.79				38.6
2.80				45.2

PROFILE, BORING 405
BASIN F

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PLATE 8

8


419
EL. 5192.6
DEPTH IN FEET
0
10
20
30
40
50
60
70
80
90
(SM-SC) dBr,
(SM) Br
(SM-SC) l Br,
(SC) l Br, G
(SP) Br, G
(SP-SM) Br, G
(SP-SM) Br, G
(SP-SM) Br, G
(SP) Br, G
(SC) Br, G, sh
(CH) Gr, S, sh
(SM) d Br, sh
(Sh) Gr, Bl, SlS
(Sh) Gr, Bl, SlS
(Sh) Gr, Bl, SlS, Cr
(MH) Bk, So, S, sh
(MH) Bk, So, S, sh
(ML) Bk, CS, S
(CH) Gr, Bl, So, SlS, sh
BLOWS PER FOOT
0 20 40 60 80 100+
WATER CONTENT, %
0 20 40 60 80
PLASTIC LIMIT
LIQUID LIMIT
NATURAL WATER CONTENT
SPECIFIC GRAVITY
2.67
2.71
2.78
2.78
2.69
2.67
2.66
2.66
2.84
2.79
2.76

% 80

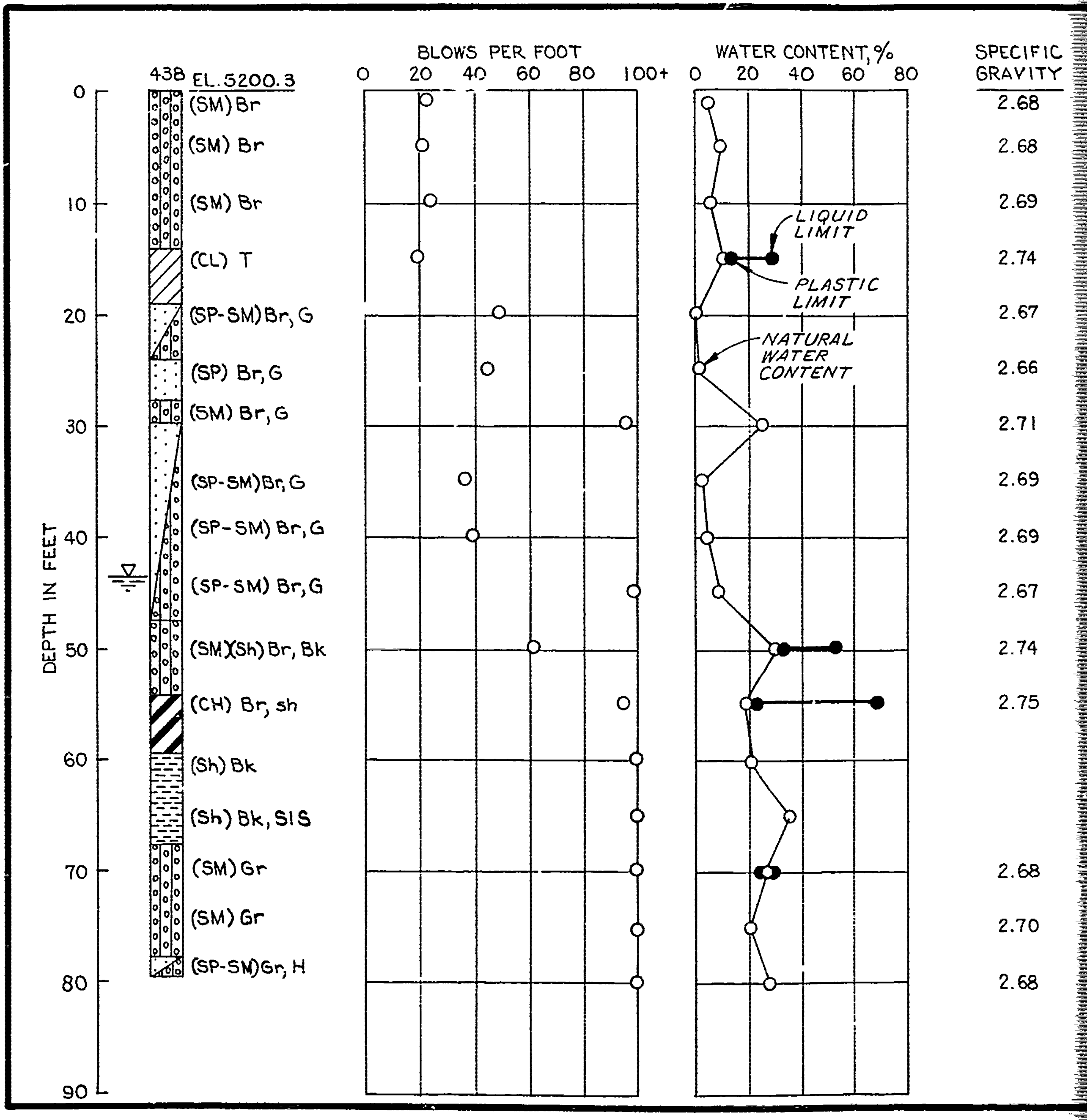
SPECIFIC GRAVITY	ESTIMATED VALUES γ_W, PCF	ϕ, DEG	C, PSF	POROSITY
2.67				
2.71	132	32	900	
2.78				
2.78				
2.69				
2.67				
2.66	132	37	950	
2.66				
2.67				
2.74				45.9
2.76				41.8
2.85				54.5
	115	15	840	
2.84				51.2
2.79				40.7
2.76				44.5

PROFILE, BORING 419
BASIN F

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PLATE 9

2



438 EL. 5200.3
DEPTH IN FEET
0
10
20
30
40
50
60
70
80
90
(SM) Br
(SM) Br
(SM) Br
(CL) T
(SP-SM) Br, G
(SP) Br, G
(SM) Br, G
(SP-SM) Br, G
(SP-SM) Br, G
(SP-SM) Br, G
(SM)(Sh) Br, Bk
(CH) Br, sh
(Sh) Bk
(Sh) Bk, SIS
(SM) Gr
(SM) Gr
(SP-SM) Gr, H
BLOWS PER FOOT
0 20 40 60 80 100+
WATER CONTENT, %
0 20 40 60 80
LIQUID LIMIT
PLASTIC LIMIT
NATURAL WATER CONTENT
SPECIFIC GRAVITY
2.68
2.68
2.69
2.74
2.67
2.66
2.71
2.69
2.69
2.67
2.74
2.75
2.68
2.70
2.68

80

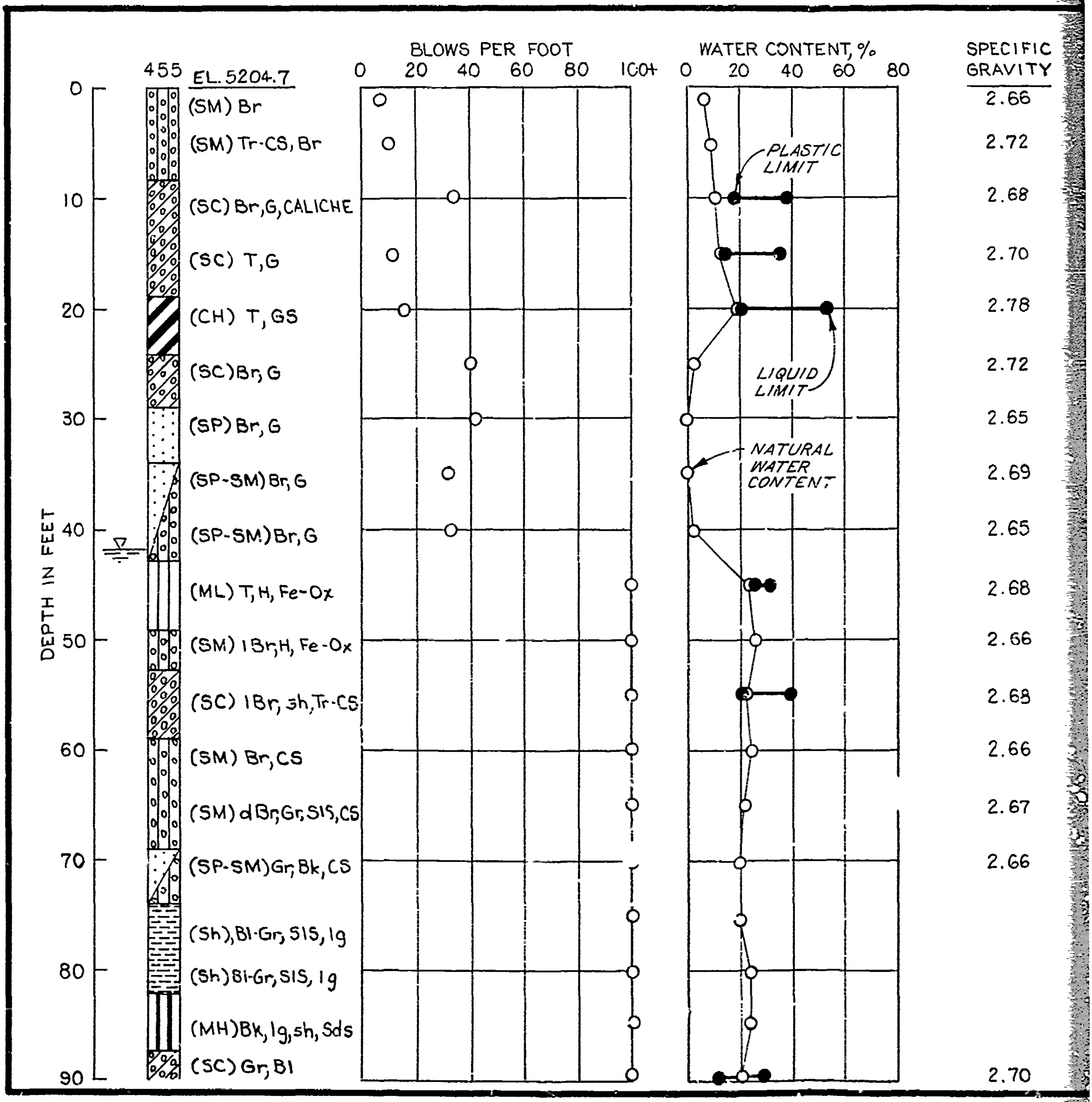
SPECIFIC GRAVITY	γ_W, PCF	ϕ, DEG	C, TSF	POROSITY
2.68				
2.68				
	132	32	900	
2.69				
2.74				
2.67				
2.66				
2.71				
	132	37	950	
2.69				
2.69				
2.67				18.8
2.74				45.4
2.75				34.2
	132	30	860	
2.68				41.1
2.70				35.6
2.68				42.3

PROFILE, BORING 438
BASIN F

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PLATE 10

2


455
EL. 5204.7
BLOWS PER FOOT
0 20 40 60 80 100+
WATER CONTENT, %
0 20 40 60 80
SPECIFIC GRAVITY
DEPTH IN FEET
0
10
20
30
40
50
60
70
80
90
(SM) Br
(SM) Tr-CS, Br
(SC) Br, G, CALICHE
(SC) T, G
(CH) T, GS
(SC) Br, G
(SP) Br, G
(SP-SM) Br, G
(SP-SM) Br, G
(ML) T, H, Fe-Ox
(SM) lBr, H, Fe-Ox
(SC) lBr, sh, Tr-CS
(SM) Br, CS
(SM) dBr, Gr, SlS, CS
(SP-SM) Gr, Bk, CS
(Sh), Bl-Gr, SlS, lg
(Sh) Bl-Gr, SlS, lg
(MH) Bk, lg, sh, Sds
(SC) Gr, Bl
PLASTIC LIMIT
LIQUID LIMIT
NATURAL WATER CONTENT
2.66
2.72
2.68
2.70
2.78
2.72
2.65
2.69
2.65
2.68
2.66
2.68
2.66
2.67
2.66
2.70

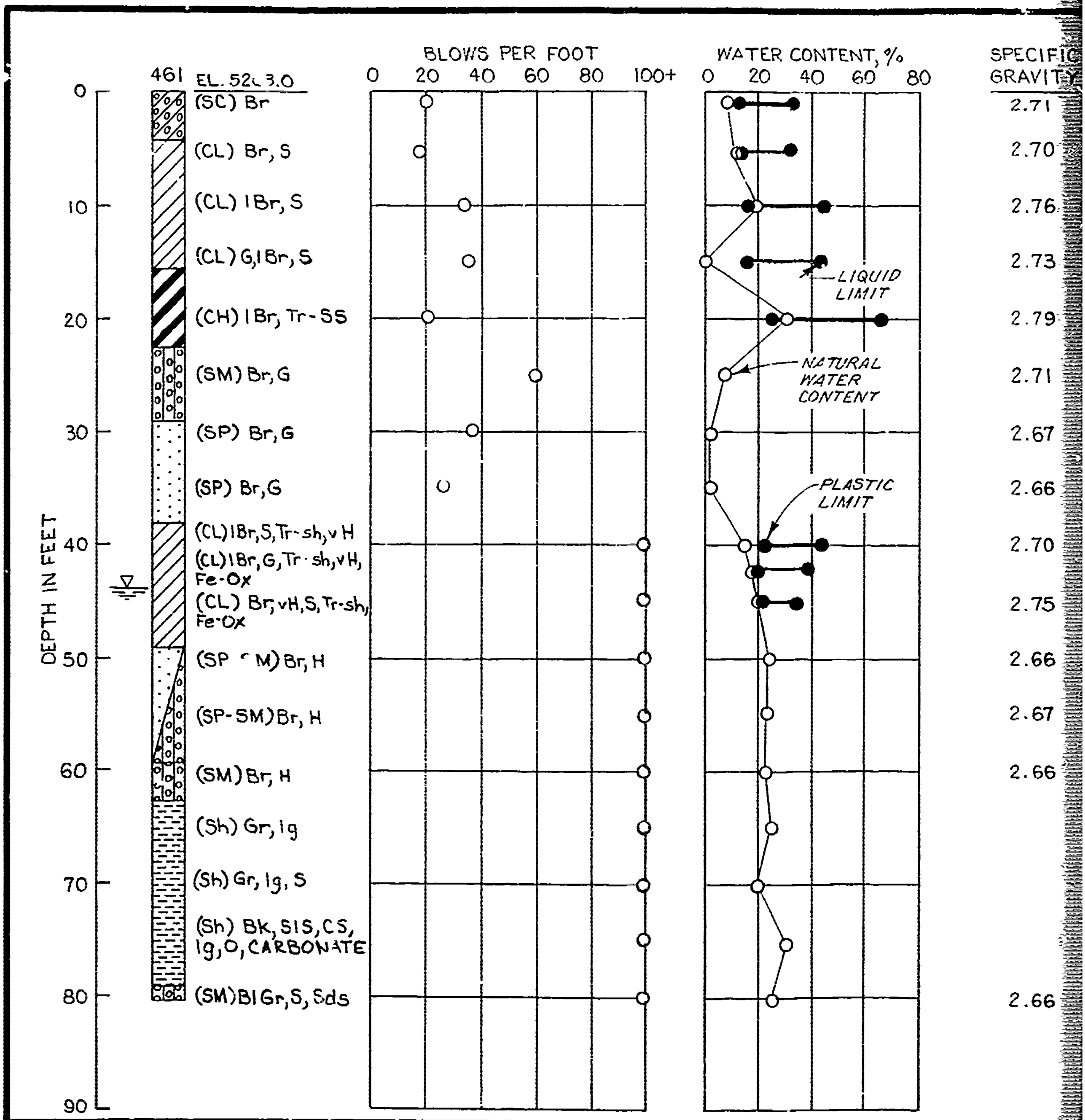
80

SPECIFIC GRAVITY	ESTIMATED VALUES γ_w, PCF	ϕ, DEG	C, PSF	POROSITY
2.66				
2.72				
2.68	115	15	840	
2.70				
2.78				
2.72				
2.65				
2.69	132	37	950	
2.65				
2.68				39.0
2.66				40.6
2.68				37.2
2.66	132	32	900	39.9
2.67				37.2
2.66				35.3
2.70				36.1

PROFILE, BORING 455
BASIN F

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PLATE II


461
EL. 52c3.0
BLOWS PER FOOT
0 20 40 60 80 100+
WATER CONTENT, %
0 20 40 60 80
SPECIFIC GRAVITY
DEPTH IN FEET
0 10 20 30 40 50 60 70 80 90
(SC) Br
(CL) Br, S
(CL) lBr, S
(CL) G, lBr, S
(CH) lBr, Tr-SS
(SM) Br, G
(SP) Br, G
(SP) Br, G
(CL) lBr, S, Tr-sh, vH
(CL) lBr, G, Tr-sh, vH, Fe-Ox
(CL) Br, vH, S, Tr-sh, Fe-Ox
(SP-SM) Br, H
(SP-SM) Br, H
(SM) Br, H
(Sh) Gr, lg
(Sh) Gr, lg, S
(Sh) Bk, SlS, CS, lg, O, CARBONATE
(SM) Bl Gr, S, Sds
LIQUID LIMIT
NATURAL WATER CONTENT
PLASTIC LIMIT
2.71
2.70
2.76
2.73
2.79
2.71
2.67
2.66
2.70
2.75
2.66
2.67
2.66
2.66

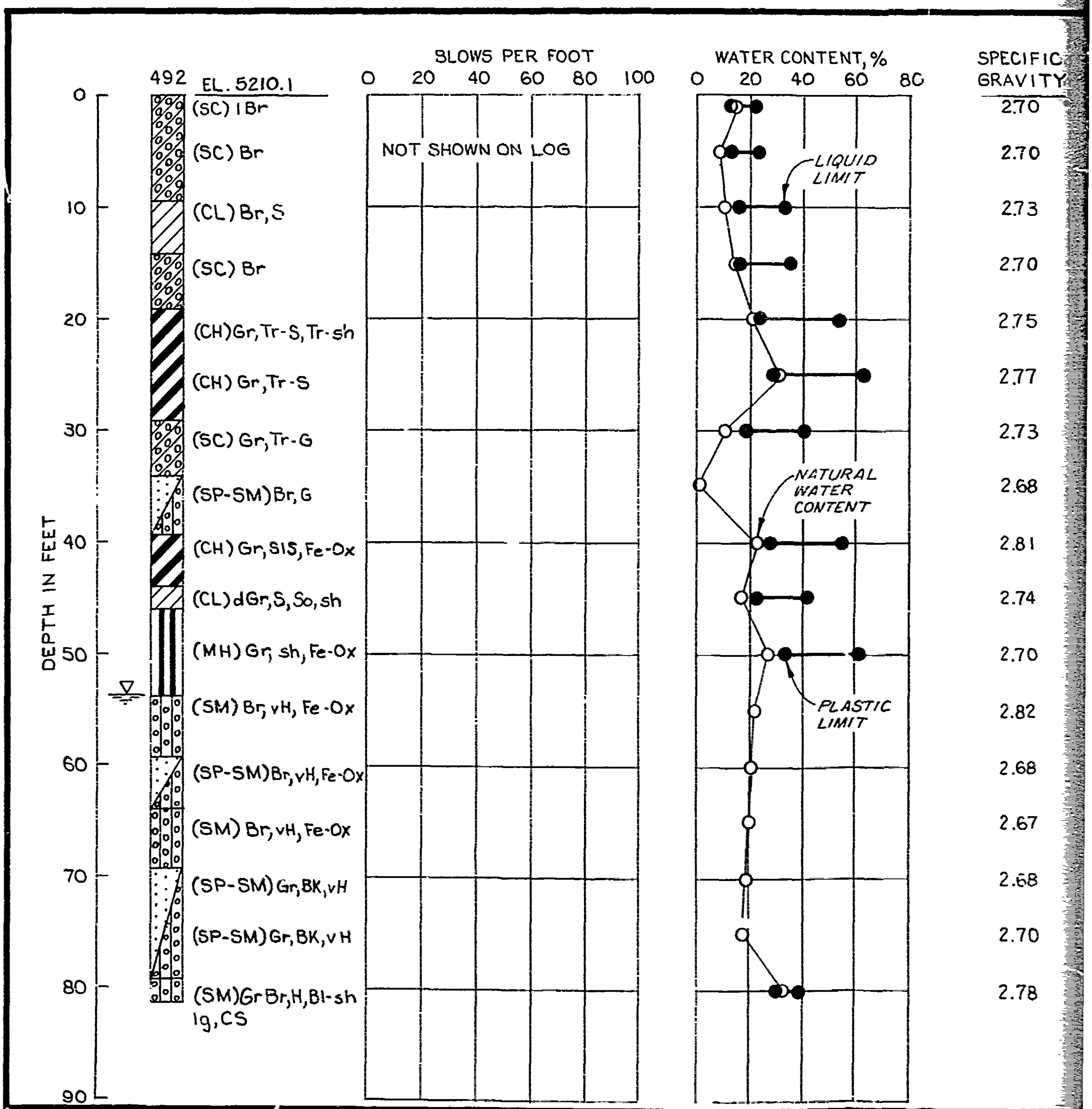
SPECIFIC GRAVITY	ESTIMATED VALUES γ_w, PCF	ϕ, DEG	C, PSF	POROSITY
2.71				
2.70				
2.76	115	15	840	
2.73				
2.79				
2.71				
2.67	132	37	950	
2.66				
2.70				
2.75	115	15	840	32.9
2.66				34.0
2.67				38.3
2.66				37.0
	132	32	900	
2.66				39.7

PROFILE, BORING 461
BASIN F

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PLATE 12

2



492
EL. 5210.1
DEPTH IN FEET
0
10
20
30
40
50
60
70
80
90
(SC) l Br
(SC) Br
(CL) Br, S
(SC) Br
(CH) Gr, Tr-S, Tr-sh
(CH) Gr, Tr-S
(SC) Gr, Tr-G
(SP-SM) Br, G
(CH) Gr, SlS, Fe-Ox
(CL) dGr, S, So, sh
(MH) Gr, sh, Fe-Ox
(SM) Br, vH, Fe-Ox
(SP-SM) Br, vH, Fe-Ox
(SM) Br, vH, Fe-Ox
(SP-SM) Gr, BK, vH
(SP-SM) Gr, BK, vH
(SM) Gr Br, H, Bl-sh lg, CS
BLOWS PER FOOT
0 20 40 60 80 100
NOT SHOWN ON LOG
WATER CONTENT, %
0 20 40 60 80
LIQUID LIMIT
NATURAL WATER CONTENT
PLASTIC LIMIT
SPECIFIC GRAVITY
2.70
2.70
2.73
2.70
2.75
2.77
2.73
2.68
2.81
2.74
2.70
2.82
2.68
2.67
2.68
2.70
2.78

80

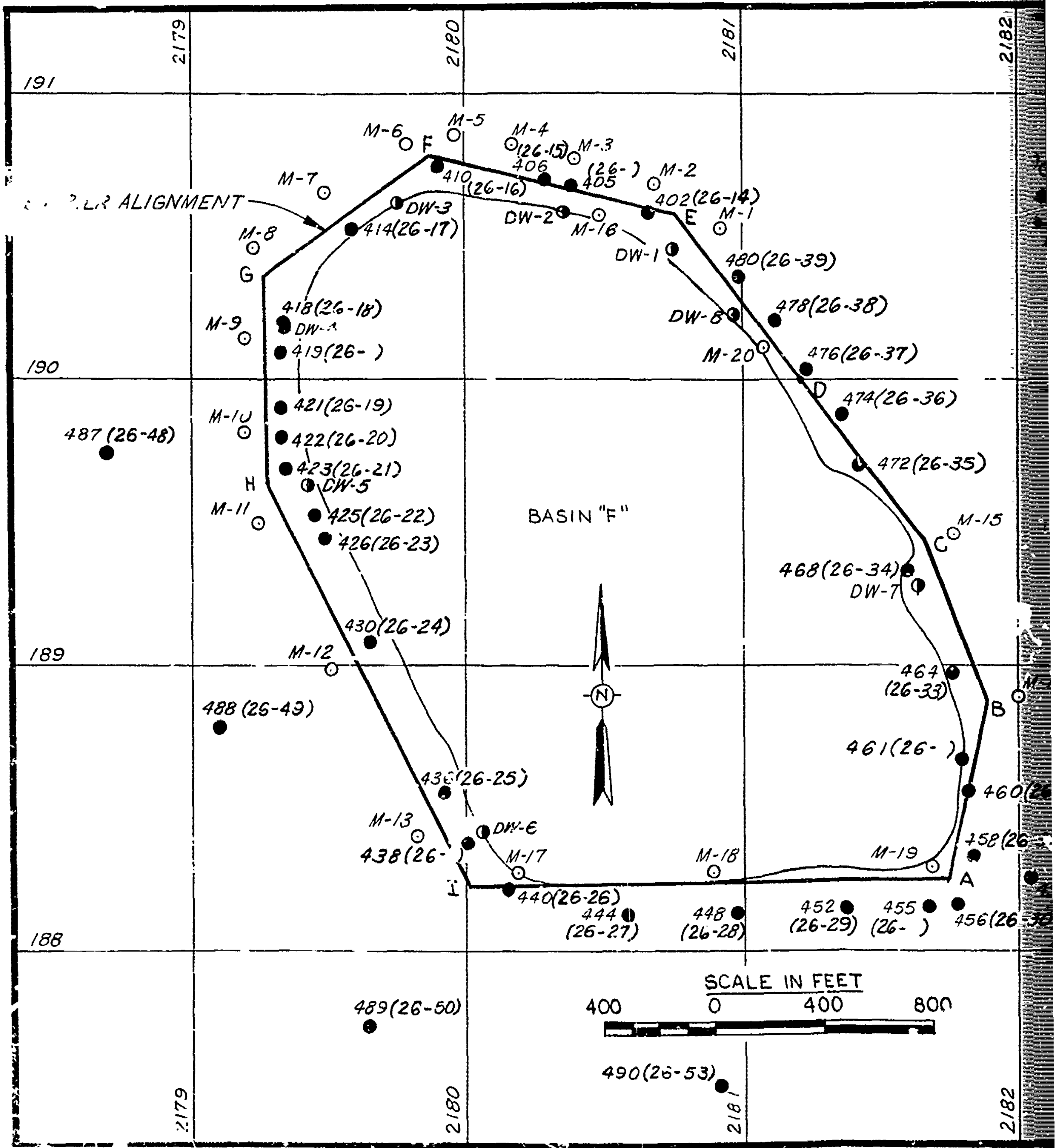
SPECIFIC GRAVITY	ESTIMATED VALUES γ_W, PCF	ϕ, DEG	C, PSF	POROSITY
2.70				
2.70				
2.73				
2.70				
2.75	115	15	840	
2.77				
2.73				
2.68				
2.81				
2.74				
2.70				41.4
2.82				38.8
2.68				36.0
2.67	132	32	900	35.0
2.68				34.7
2.70				32.6
2.78				47.8

PROFILE, BORING 492
BASIN F

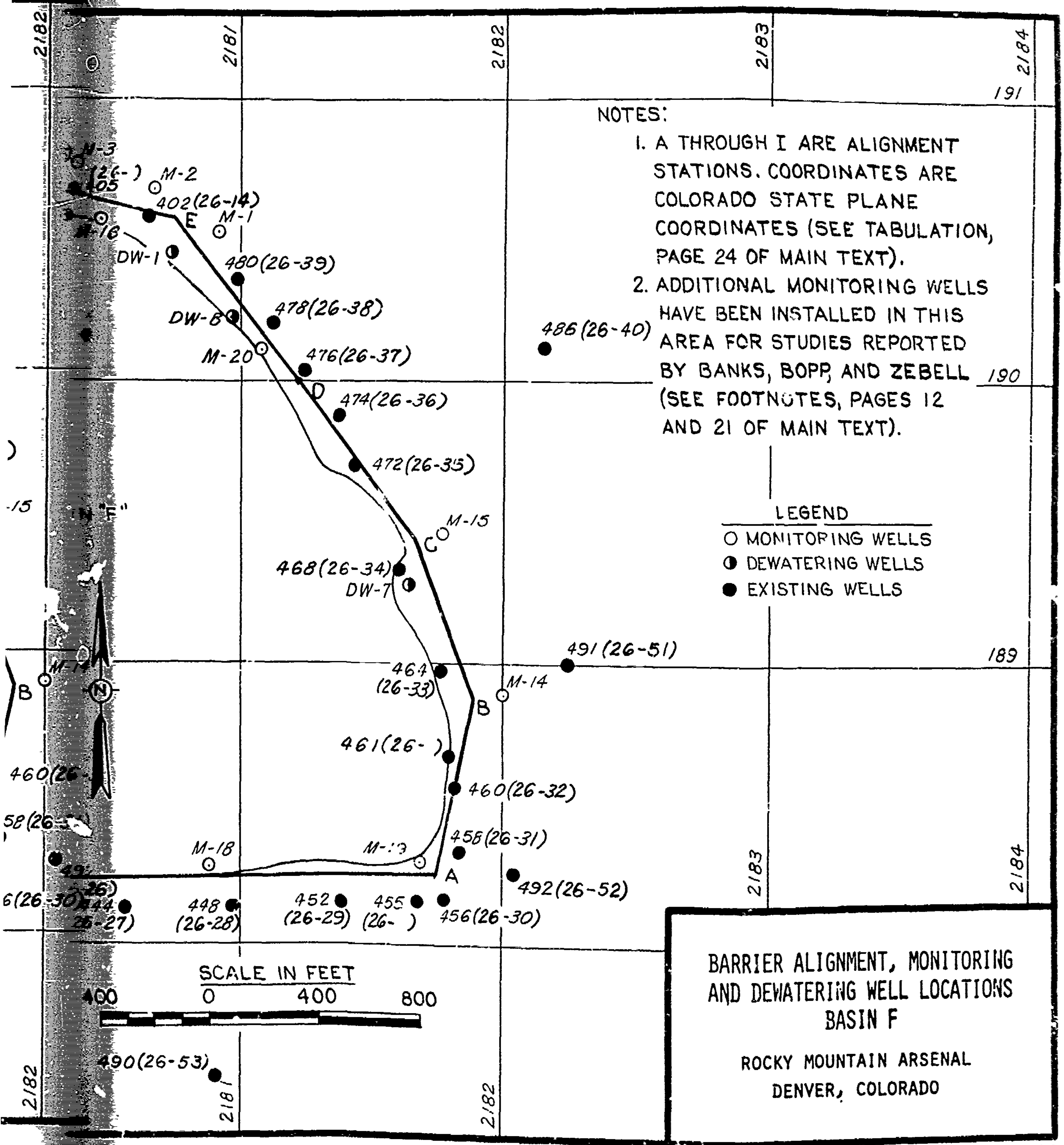
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PLATE 13

2



2179
2180
2181
2182
191
190
189
188
BASIN "F"
ALIGNMENT
SCALE IN FEET
400 0 400 800



BARRIER ALIGNMENT, MONITORING AND DEWATERING WELL LOCATIONS
BASIN F

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PLATE 14

APPENDIX A: COMPATIBILITY STUDIES

Introduction

1. Because of the assumed corrosive qualities and very limited knowledge about the detrimental effects of Basin F fluid and its dilutions on any construction material, the initial Basin F containment report* recognized the need for compatibility studies. A review was made to determine compatilibity studies as described on pages A4 through A9; then, a compatibility study program was developed through the cooperative effort of WES, RMA, and USATHMA. This program consists of two separate studies, one on bentonite slurry trench materials and the second on engineering and construction materials.

2. Testing of bentonite backfill mixtures was started in the summer of 1978 with D'Appolonia Consulting Engineers, Inc., Pittsburgh, Pennsylvania. This program, with a test duration of 100 days, evaluated various bentonite-soil and bentonite-cement trench backfill mixtures for a short term (approximately 100 days). A longer duration test of the best candidates from the short-term study is under way. Results indicate that a one-half dilution of Basin F fluid has no significant effect on the permeability of the backfill mixtures and that there are no significant differences between the permeability of the specimens subject to waste flow and the control specimen subject to flow of distilled water. The only apparent effect is in the two cement bentonite specimens, 1 and 7, which show a slight increase in permeability after three weeks of flow though the permeabilities have stabilized since that change. The permeabilities fall within the range expected for slurry trenches, 10^{-6} to 10^{-8} cm/sec. The test setup was observed and discussed during October 1978 by Messrs. D. Campbell and J. Zarzyki of PMO CDIR and S. P. Miller of WES. It was noted that the color of the one-half dilution of Basin F fluid faded considerably after passage through the specimens, particularly those with higher percentages of CL soil and the cement bentonite mixtures. Chemical analysis is being made of the

* Rendon, op.cit. (See footnote on page 8 of main text.)

one-half dilution Basin F fluid and the effluent from the specimens; these results will be reported with the longer duration study being conducted by D'Appolonia Consulting Engineers, Inc.

3. During August 1978, the Structures Laboratory (SL), WES, was asked to conduct a laboratory study of the effects of Basin F fluid on bentonite slurry as used during construction to maintain an open trench between the excavation and backfilling operations. The resulting report, "Flocculation Test of 5% Bentonite Clay Treated with RMA Waste," submitted by Mr. T. Husbands (SL), is as follows:

<u>a</u>. Two liters of a 5% bentonite clay slurry were prepared by mixing 100 g of the bentonite clay into 1900 g of distilled water. Seventy-five mℓ of the slurry was added to each of nine test tubes. Different amounts of the RMA waste liquid were then added to the test tubes containing the slurry, mixed, and allowed to stand for 7 days in the laboratory.

<u>b</u>. No flocculation was observed after 7 days, however, the test tubes containing the larger amounts of RMA waste did appear to thicken. Viscosity measurements were made using a Brookfield viscometer model LVF. A number 3 spindle set at 30 rpm was used to determine the viscosities. The results are shown in Figure A1 and Table A1.

<u>c</u>. The density of the clay slurries was determined by weighing the test tubes, then marking the volume on the tubes. The tubes were cleaned, and distilled water put into the tubes to the mark to determine the volume. Results are shown in Table A2.

As indicated above, the injection of Basin F fluid in increasing percentages up to about 2.5 percent increases the viscosity of the slurry, while for higher percentages of the fluid the viscosity appears to stabilize. While the mixtures with a higher percentage of Basin F fluid appeared to "gel," there was no settling out of the bentonite from the mixture. This effect is being studied in the longer term program of bentonite compatibility testing. It is felt that the SL testing was somewhat severe since full-strength Basin F fluid was injected into the slurry; whereas in field conditions the slurry will move from the trench out into the polluted aquifer (this distance will be very small. but the movement will be of the slurry outward from the trench) and the polluted aquifer will have a much diluted form of Basin F fluid.

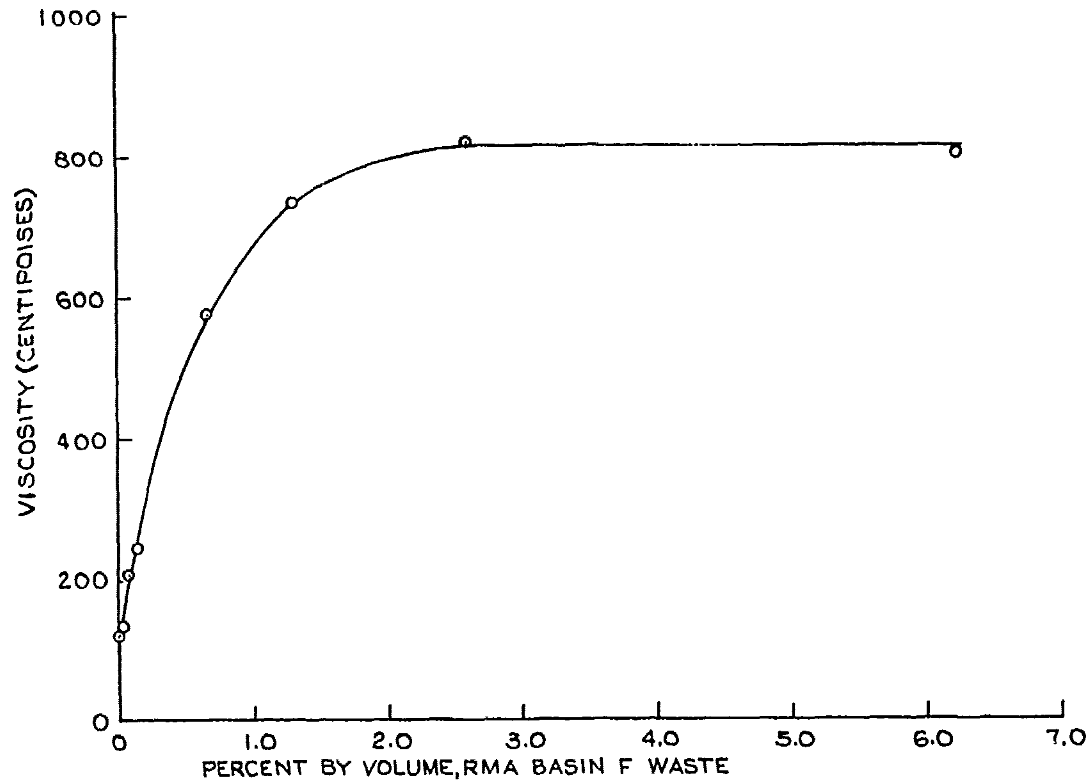


Figure A1. Effect of injected Basin F waste on bentonite slurry viscosity

Table A1

Viscosity of 5% Bentonite Clay Slurry

Volume RMA Waste Added, mℓ	%, RMA Waste by Volume	Viscosity, cps
0.00 (Control)	0.00	125
0.01	0.01	136
0.025	0.035	Not reported
0.05	0.07	208
0.10	0.13	244
0.50	0.66	576
1.00	1.31	732
2.00	2.60	820
5.00	6.25	800

Table A2

Density of 5% Bentonite Clay Slurry

Volume RMA Waste, %	Specific Gravity, g/cc
0.00 (Control)	1.039
0.01	1.028
0.035	1.044
0.07	1.025
0.13	1.054
0.66	1.065
1.31	1.053
2.60	1.017
6.25	1.047

4. During September 1978, Mr. Carl Loven, RMA, with Mr. S. P. Miller, WES, developed a compatibility study plan for engineering and construction materials. Results were presented in a contract report prepared by Matrecon, Inc. (1978). A longer duration exposure test program with "best candidates" from short-term testing is under way.

5. In summary, the compatibility study program for Basin F containment consists of two parts: (a) bentonite slurry and (b) engineering and construction materials. Each area has been evaluated with short-term studies and is being followed by longer term studies based on short-term results and containment designer needs known at the long-term study design stage.

Compatibility Studies Review

The Engineering Group, Soil Mechanics Division, Geotechnical Laboratory, of WES was tasked to develop design, reliability, and cost data for selected containment options for Basin F, Rocky Mountain Arsenal (RMA), Commerce City, Colorado. The characteristics (design, cost, and reliability data) of a particular option would be directly related to the existence and degree of detrimental effect of Basin F fluid on construction materials used in each option. Thus, studies of compatibility between Basin F fluid and the various construction

materials for the selected options would provide some of the most important input used in determining the general characteristics of each option.

The purpose of the compatibility study was to determine, in the laboratory, what effect Basin F fluid would have on the integrity of selected construction materials over a period of time. The object of this paper was to develop the background for and outline of a program of compatibility testing of construction materials for containment of Basin F.

Previous studies

Two previous papers have reported studies of the effects of Basin F fluid on various liner materials, well tubing, and mild steel.

The first study was performed in 1960 by the Dow Chemical Company Materials Engineering Laboratory. This study was made to determine the corrosivity of the wastewater on well tubing for a proposed disposal well and SAE 1018 mild steel under different degrees of aeration. It was desired to demonstrate the effect of deaeration in reducing the corrosion rate. Rates in the laboratory for the well tubing and mild steel were: 1.6 to 1.8 mpy (mils per year) deaerated and 15.4 to 19.2 mpy aerated. The duration of these tests was not reported, but it was stated, "It appears that with this waste solution, the rate in piping would be considerably higher than 20 mpy." It continues, "...Corrosion in pumps would be still greater because of the high velocity and resulting turbulence. For this reason, pumps would have to be made of corrosion resistant alloys to operate more than several months under aerated conditions. Deaeration, on the other hand, should result in satisfacto.y life of pumps and piping as well as reducing corrosion of the well casing. Deaeration can be accomplished mechanically or by additions of catalyzed sodium sulfite or hydrazine. Care should be taken to prevent subsequent air pickup through leaks in pump glands or at other points of negative pressure."

The second study, "Results of Test Program for Candidate Liner Materials for New Rocky Mountain Arsenal Basin," was conducted in 1970 by the Bureau of Reclamation, Denver, Colorado. The object of this

study was to determine the effects of a mixture of Basin F waste and a simulated industrial waste on three rubber and two plastic lining materials (asphalt lining was not tested because it was not considered suitable for the proposed installation since detrimental hydrocarbons were expected in the waste to be stored). Tests performed included waste immersion, soil burial, and subjection to a 4-ft hydrostatic head of the simulated waste. The waste immersion test lasted 30 days, while the hydrostatic-head test lasted approximately 55 days. Soil burial samples were placed in a soil of high microbiological activity for 30 days. The conclusions stated, "Based on the short-term tests completed on the different candidate liners for RMA basin, there is no evidence to indicate that any one of the lining materials tested would be seriously affected by the ponded waste." A later letter concerning this study reported that the hydrostatic-head tests had been continued for an additional 58 days without leakage through any of the liner specimens. Information was given on testing of a catalytically blown asphalt membrane, and the following summation presented:

> The additional test results obtained to date have not revealed any information that would give cause for revising conclusions reported in our September 23, 1970 letter. It is indicated that the catalytically blown asphalt membrane has disadvantages because of its incompatibility with hydrocarbons and hydrocarbon derivatives. The nylon-reinforced neoprene membrane appears questionable because of high absorption and volume swell. The best candidate liners appear to be the standard PVC, Hypalon, and nylon-reinforced butyl.

Background

Several testing laboratories, universities, chemical companies, and government agencies were contacted to determine where similar compatibility-type testing was done. Additionally, reports concerning the effects of various wastes on different materials were reviewed. A bibliography is included at the end of this paper, and a list of people and organizations contacted during development of the compatibility study plan is in the project files at WES.

Compatibility studies for waste storage area construction materials normally expose the candidate materials to the expected waste

with periodic observations made and physical properties determined for comparison with pretest properties. Most materials tested are either liner/membranes or admixes (asphalt soil, soil cement, bentonite, lime stabilized soil, etc.). Most testing has been of relatively short duration, i.e., one year or less, and predictions for long periods from this testing are not given a high degree of confidence by the experimenters. Factors other than laboratory waste exposure may be important to the effective functioning of the construction material. These include temperature changes, erosion, sun exposure (ultraviolet rays), etc. The Environmental Protection Agency (EPA) has funded exposure-type testing for industrial and municipal wastes with one project having a duration of three years. Most tests are performed in a vertical cylindrical or rectangular permeameter-type device that contains the waste at a specified depth above the construction material specimen that is fixed to the bottom of the device. Periodic observations are made of the bottom of the material to ascertain if any waste has penetrated. Strength, elongation, swell, brittleness, and permeability evaluations (as applicable to particular materials) are made on the material during the exposure test and compared with values of these properties prior to testing. Seams and joints are evaluated in like manner. Samples of the materials may also be suspended in the waste above the primary test specimen and removed periodically for observation and testing.

A recent (1977) book, Construction of Linings for Reservoirs, Tanks, and Pollution Control Facilities, indicates that oxidizing acids and solvents are of primary concern in the use of all common linings. Again it appears that laboratory testing can only be used as a guide; thus, a double-lining system with a "sandwiched" drain is recommended as a "fail safe" design. The drain system should be so designed that any leaks in the first lining can be identified by area, the escaped waste returned to the basin, and repairs made. Compartmentalization of the basin and the drain system make leak location and repair easier.

The review, contacts with experimenters, and engineering judgment indicate that an exposure-type test of long duration would be best to determine the compatibility of Basin F fluid with various

construction materials. The compatibility tests may not be indicative of material performance if the chemistry or concentration of Basin F fluid changes from that used in the compatibility program. Also other factors, such as erosion, temperature change, wetting-drying cycles, and sun exposure that can influence performance of materials, are not normally evaluated in long-term tests because of expense. These factors would not normally be encountered in a below surface installation.

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In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Miller, Samuel P
  Geotechnical containment alternatives for industrial waste Basin F, Rocky Mountain Arsenal, Denver, Colorado; a quantitative evaluation / by Samuel P. Miller. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1979.
  50, 9 p., 14 leaves of plates : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; GL-79-23)
  Prepared for Contamination Control Directorate, Rocky Mountain Arsenal, Commerce City, Colorado, under Intra-Army Order No. RM 56-78.
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